UNIVERSITAT ROVIRA I VIRGILI

MATERIAL FLOW ANALYSIS AND ENVIRONMENTAL IMPACT ASSESSMENT OF THE CONSTRUCTION SECTOR IN BRAZIL

Karina de Macedo Soares Pires Condeixa

DOCTORAL THESIS

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Department of Mechanical Engineering

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Summary

The recent discussions and research on climate change created an awareness of the need for balance between urban development and the natural environment. The dematerialization has been considered indispensable to reduce environmental pressures, to avoid scarcity of natural resources and to reduce climate change, but still allowing the development of human activities.

The extensive use of materials in building stocks contributes to the scarcity of natural resources and waste disposal on the environment. The construction industry and governments are joining efforts to promote sustainability and efficiency in the use of materials through mapping, analysis and improvement of performance. Material Flow Analysis (MFA) has been used as a tool to achieve dematerialization and sustainability of building stock.

MFA is a methodology that survey material stocks and flows. It has been used in different fields of studies in different scales, applications and methods. This large range of approaches on MFA tends to generate bad understanding and therefore hinders the systematic use of this methodology.

Brazil has sought to adjust to the global trends of sustainability; Brazilian policies started encouraging the use of material flow analysis and life cycle assessment of products as tools to improve the management of solid waste, sustainable consumption to reduce the impacts from the streams and waste treatments.

This thesis applied MFA to discover the materials in a building stock in a Brazilian city and their material and waste flows. MFA combined to LCA assessed impacts from their waste flows.

The work developed in this PhD research and compiled in this dissertation is presented in three chapters: chapters 2, 3 and 4. Chapter 2 promotes a literature review and a bibliometric analysis supporting the systematic use of Material Flow Analysis. Chapter 3 proposes a method based on Material Flow Analysis to model the residential building stock in the city of Rio de Janeiro and their material and waste flows, in order to characterize the stock. Chapter 4 introduces the methodologies MFA and Life Cycle Assessment combined to model waste flows from a building stock and to assess its life cycle impacts.

In broad details, chapter 2 aims give a comprehensive understanding to enable a systematic application of the MFA methodology through literature review and bibliometric study. The literature review is done from the creation and development of MFA, as methods, applications, and strategies for sustainability. The bibliometric study analyzes trends of publications by expressions, authors, countries, methods and impact factor. Overall, this chapter contextualizes MFA, presents and discusses specificities of methods and goals to be achieved, identifies partnerships between researchers and trends in publications. This chapter aims to provide a broad understanding of the development and purposes of the MFA and assist in the systematic application of this methodology.

Chapter 3 models and assess the residential building stock in the city of Rio de Janeiro, and their material and waste flows, between 2010 and the end of its life. It uses a method based on Material Flow Analysis with a bottom-up approach. Using this method, the study surveys the materials intensities in function of models type of residential buildings in Brazil and extrapolate them to the total constructed area of the residential building stock. In addition, it analyses the amount and type of buildings are in the stock and predict its mortality time. Results show that the amount of material in stock in 2010 is around 78,828,773t with material intensity between 2.58 and 0.74t/m^2, concrete and aggregates having the higher material intensity. Single-family houses are the most common types of buildings; however, multi-family buildings accommodate most families. The use phase tends to move at least 9,807,694t until 2090. Our findings can help decision-makers planning strategies for construction and demolition waste management focused on the sustainability in the use of materials and treatment of waste.

Chapter 4 models the waste flows considering the new waste policies, as well as, assesses the environmental impact of the life cycle, considering most representative materials in building stock. MFA is used to analyse the waste flows and LCA is used to assess the impacts of the waste flows. The materials flows are modelled based on waste policies, statistical data and literature. This LCA, specifically in the LCIA phase, identifies the impact of greenhouse gases emissions using IPCC2013 method, and the impacts of ReCipe2008. Results highlighted a high potential of water depletion and human toxicity impacts from waste disposal in landfills, and potential of global warming, climate changes and fossil depletion from waste recycling. Recycling processes are very pollutant, but we depend on the recycling to achieve the dematerialization of the construction sector and the preservation of natural resources for future generations. Consequently, it is necessary promote a conscious consumption, with an efficient use of materials and management of waste to achieve the balance between nature and development.

In summary, this thesis highlights on the variants of the Material Flow Analysis methodology to promote a broadly analysis of a building stock. The main objectives of this research are: to discover how MFA methodology has been used to inventory building stocks; to characterize the building stock and its flows, compared to stocks in other countries; and to identifying the impacts of different processes in the waste streams. Finally, we point out alternatives to assist the decisions makers in create strategies to the dematerialization of development.

Resumen

Después de discusiones e investigaciones sobre impactos del cambio climático y del desarrollo del hombre sobre el medio ambiente, fue estableciendo la conciencia de la necesidad de tener un equilibrio entre desarrollo urbano y el medio ambiente. La desmaterialización se ha considerado esencial para reducir las presiones ambientales, evitar la escasez de recursos naturales y frenar el cambio climático, sino que también permite el desarrollo de las actividades humanas.

El uso extensivo de materiales en la construcción de edificios de poblaciones contribuye a la escasez de los recursos naturales y la eliminación de los residuos en el medio ambiente. La industria de la construcción y los gobiernos están uniendo fuerzas para promover la sostenibilidad y la eficiencia en el uso de materiales a través del mapeo, análisis y mejora de las actividades relacionadas con el desempeño de los edificios.

La metodología de Análisis de Flujo de Materiales (MFA) se ha utilizado como una herramienta para lograr la desmaterialización y la sostenibilidad. MFA es una metodología que identifica los flujos de materiales y los materiales acumulados. MFA se ha utilizado en diferentes campos de estudios en diferentes escalas, aplicaciones y métodos. Esta amplia gama de enfoques MFA tienden a generar malentendidos y evitar así el uso sistemático de esta metodología.

Brasil está tratando de adaptarse a las tendencias globales de sostenibilidad; políticas brasileñas han sido alentadores análisis de los flujos de materiales y la evaluación del ciclo de vida del producto como herramientas para mejorar la gestión de residuos sólidos, fomentar el consumo sostenible y reducir al mínimo los impactos procedentes de los arroyos y tratamiento de residuos.

En esta tesis se aplica MFA para descubrir los materiales contenidos en los edificios residenciales de una ciudad en Brasil y los flujos que resultan de ella, y se utiliza en combinación con MFA y LCA para analizar el impacto de los flujos de residuos.

El trabajo desarrollado en esta tesis doctoral y que esta compilado en este trabajo se presenta en tres capítulos: los capítulos 2, 3 y 4. El capítulo 2 es una revisión bibliográfica y un análisis bibliométrica para apoyar el uso sistemático de la utilización de la metodología de análisis de flujo de materiales. Capítulo 3 propone un método basado en el análisis del flujo de materiales para modelar el stock de edificios residenciales en la ciudad de Río de Janeiro y sus

materiales y flujos de residuos con el fin de caracterizar el parque de edificios. El capítulo 4 presenta las metodologías de Análisis de Flujo de Materiales y Análisis de Ciclo de Vida combinados para modelar el flujo de residuos procedentes de las existencias de edificios y evaluar los impactos del ciclo de vida.

Con más detalle, el capítulo 2 tiene como objetivo dar una comprensión global para permitir una aplicación sistemática de la metodología de MFA a través de una revisión de la literatura y de un estudio bibliométrico. La revisión de la literatura se hace de la creación y el desarrollo MFA, como métodos, aplicaciones y estrategias de sostenibilidad. El estudio bibliométrico analiza las tendencias de las publicaciones de expresiones, autores, países, métodos y factor de impacto. En general, este capítulo contextualiza MFA, presenta y discute los métodos y los objetivos específicos que deben alcanzarse, identifica las asociaciones entre los investigadores y las publicaciones de tendencias. Este capítulo tiene como objetivo proporcionar una amplia comprensión de los acontecimientos y propósitos de la MFA y ayudar en la aplicación sistemática de esta metodología.

Capítulo 3 modela y evalúa las acciones de los edificios residenciales en la ciudad de Río de Janeiro, y los materiales y los flujos de residuos, entre 2010 y el final de su vida, por un método basado en el análisis de flujo de materiales con un enfoque "*bottom-up*". Usando este método, este estudio identifica las intensidades de los materiales en función de modelos tipo de edificios residenciales en Brasil y extrapolan a la superficie construida total de la población de edificio residencial. Además, se analiza la cantidad y tipo de edificios están en la acción y predecir su tiempo de la mortalidad.Los resultados muestran que la cantidad de material del parque en 2010 se trata de 78,828,773t , con intensidad de materiales entre 2,58 y 0,74 t/m^2 ; el hormigón y los agregados tienen las mayores intensidades de materiales. Las viviendas unifamiliares son la mayoría de los tipos de edificios. Sin embargo, los edificios multifamiliares admiten la mayoría de las familias. Los edificios utilizan fase tiende a moverse al menos 9,807,694t de 2090. Nuestros resultados pueden ayudar a tomar decisiones para la planificación de estrategias para la construcción y la gestión de los residuos de demolición centrado en la sostenibilidad en el uso de materiales y tratamiento de residuos.

Capítulo 4 modela los flujos de residuos teniendo en cuenta las nuevas normas de desecho y evalúa el impacto ambiental del ciclo de vida, teniendo en cuenta los valores de materiales edificios más representativos. MFA se utiliza para analizar los flujos de residuos y LCA se utiliza para evaluar el impacto de los flujos de residuos. Los flujos de materiales son modelados sobre la base de la política de residuos, las estadísticas y la literatura. Esta análisis de los impactos de ciclo de vida identifica el impacto de los gases de efecto invernadero (GWP) utilizando el método IPCC2013, y los impactos del método ReCipe2008. Los resultados muestran un alto índice potencial de impacto de agotamiento del agua y su toxicidad humana por sumergir residuos en los vertederos y los potenciales impactos de gases de efecto invernadero, el cambio climático y el agotamiento de los combustibles fósiles mediante el reciclaje de residuos. Los procesos de reciclaje son muy contaminantes, pero el reciclaje es importante para lograr la desmaterialización del sector de la construcción y para la preservación de los recursos naturales para las generaciones futuras. Por lo tanto, es necesario que promovemos un consumo consciente, el uso eficiente de los materiales y la gestión de residuos para lograr un equilibrio entre la naturaleza y el desarrollo.

En resumen, esta tesis explica las variantes de la metodología de análisis de flujo de materiales y promueve un análisis amplio de un parque de edificio residencial. Los principales objetivos de esta investigación son: averiguar cómo la metodología MFA se ha utilizado para las existencias del inventario de edificios; caracterizar la acumulación de materiales y su flujo de residuos en comparación con los parques de edificios residenciales de otros países; e identificar los impactos de los diferentes procesos en los flujos de residuos. Por último, este estudio destaca alternativas para ayudar a los tomadores de decisiones en estrategias para la desmaterialización de desarrollo.

Resumo

Após debates e pesquisas sobre mudanças climáticas, institui-se a consciência da necessidade de ter equilíbrio entre o desenvolvimento urbano e o ambiente natural. A desmaterialização vem sendo considerada indispensável para diminuir as pressões ambientais, evitar a escassez de recursos naturais e frear as mudanças climáticas, mas ainda permitindo o desenvolvimento das atividades humanas.

O uso extensivo de materiais na construção de estoques de edifício contribui para a escassez de recursos naturais e a eliminação de resíduos no meio ambiente. A indústria da construção civil e os governos vêm unindo esforços para promover a sustentabilidade e a eficiência no uso de materiais por meio de mapeamento, análises e melhoria das atividades relacionados ao desempenho dos edifícios.

A metodologia de Análise de fluxos de Materiais (MFA) vem sendo usada como uma ferramenta para alcançar a desmaterialização e a sustentabilidade. MFA é uma metodologia que inventaria fluxos e estoques de materiais. MFA tem sido utilizada em diferentes campos de estudos, em diferentes escalas, aplicações e métodos. Este grande leque de enfoques de MFA tendem a gerar má compreensão e, portanto, impedir a utilização sistemática desta metodologia.

O Brasil vem buscando se se adequar as tendências globais de sustentabilidade; as políticas brasileiras vêm incentivando analises de fluxos de materiais e avaliação do ciclo de vida de produtos como ferramentas para melhorar a gestão dos resíduos sólidos, incentivar o consumo sustentável e minimizar os impactos oriundos dos fluxos e tratamentos dos resíduos.

Esta tese aplicou MFA para descobrir os materiais contidos em um estoque de edifícios de uma cidade no Brasil e os fluxos dele resultantes, e usou MFA combinado com LCA para analisar os impactos dos fluxos de resíduos.

O trabalho desenvolvido nesta pesquisa de PhD e compilado nesta dissertação é apresentado em três capítulos: capítulos 2, 3 e 4. O capítulo 2 faz uma revisão de literatura e uma análise bibliométrica para subsidiar o uso sistemático uso da metodologia de Análise de Fluxos de Materiais. O capítulo 3 propõe um método baseado em Analise de Fluxos de Materiais para modelar o estoque de edifícios residenciais na cidade do Rio de Janeiro e seus fluxos de materiais e resíduos, no intuito de caracterizar o estoque de edifícios. O capítulo 4 introduz as metodologias de Análise de Fluxos de Materiais e de Avaliação do Ciclo de Vida

combinadas para modelar os fluxos de resíduos oriundos do estoque de edifícios e avaliar os seus impactos do ciclo de vida.

Em maiores detalhes, o capítulo 2 tem como objetivo dar uma compreensão abrangente para permitir uma aplicação sistemática da metodologia MFA por meio de uma revisão da literatura e um estudo bibliométrico. A revisão da literatura é feita a partir da criação e desenvolvimento de MFA, como métodos, aplicações e estratégias de sustentabilidade. O estudo bibliométrico analisa as tendências das publicações por expressões, autores, países, métodos e fator de impacto. No geral, este capitulo contextualiza MFA, apresenta e discute especificidades de métodos e objetivos a serem alcançados, identifica parcerias entre pesquisadores e tendências em publicações. Este capítulo visa fornecer uma ampla compreensão dos seus desdobramentos e propósitos da MFA e auxiliar na aplicação sistemática desta metodologia.

O capítulo 3 modela e avalia o estoque de edifícios residenciais na cidade do Rio de Janeiro, e os seus fluxos de materiais e resíduos, entre 2010 e o final de sua vida, através de um método baseado em Análise de Fluxo de Materiais com uma abordagem "*bottom-up*". Usando esse método, este estudo identifica as intensidades de materiais em função de edifícios modelos, típicos de edifícios residenciais no Brasil e extrapolá-las para a área total construída da unidade populacional de edifício residencial. Além disso, este estudo analisa a quantidade e os tipos de edifícios no estoque e faz uma previsão do seu tempo de mortalidade dos edifícios. Os resultados mostram que a quantidade de material em estoque em 2010 é de cerca de 78,828,773t com intensidade material entre 2,58 e 0,74 t/m^2, sendo que o concreto e os agregados possuem a maior intensidade material. As casas unifamiliares são a maioria dos tipos de edifícios; no entanto, edifícios multifamiliares acomodam a maioria das famílias. A fase de uso dos edifícios tende a movimentar, pelo menos, 9,807,694t até 2090. Nossas descobertas podem ajudar as decisões para as estratégias de planejamento para a construção e gestão de resíduos de demolição focada na sustentabilidade no uso de materiais e tratamento de resíduos.

Capítulo 4 modela os fluxos de resíduos considerando as novas normas de resíduos, bem como, avalia o impacto ambiental do ciclo de vida, considerando os materiais mais representativos edifícios de ações. MFA é utilizado para analisar os fluxos de resíduos e ACV é usado para avaliar os impactos dos fluxos de resíduos. Os fluxos de materiais são modelados com base em políticas de resíduos, dados estatísticos e literatura. Esta Analise de Impactos do Ciclo de Vida identifica o impacto das emissões de gases de efeito estufa utilizando o método IPCC2013, e os impactos do método ReCipe2008. Os resultados evidenciam uma alta taxa de

potencial de impacto para esgotamento da água e toxidade humana por despejo de resíduos em aterros e dos impactos de gases de feito estufa, mudanças climáticas, e esgotamento de combustíveis fosseis pela reciclagem de resíduos. Os processos de reciclagem são muito poluentes, mas as reciclagens são importantes para atingirmos a desmaterialização do sector da construção e para a preservação dos recursos naturais para as gerações futuras. Por conseguinte, é necessário promovermos um consumo consciente, com um uso eficaz de materiais e de gestão de resíduos para alcançar o equilíbrio entre a natureza e desenvolvimento.

Em resumo, esta tese esclarece as variantes da metodologia de Análise de Fluxos de Materiais e promove uma análise ampla de um estoque de edifício. Os principais objetivos desta pesquisa são: descobrir como a metodologia MFA tem sido usada para inventários estoques de edifícios; caracterizar o estoque de edifício e os seus fluxos, em comparação com os estoques em outros países; e identificar os impactos dos diferentes processos nos fluxos de resíduos. Por fim, este estudo destaca alternativas para ajudar os tomadores de decisões na elaboração de estratégias para a desmaterialização do desenvolvimento.

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1 INTRODUCTION

1.1 Sustainable development

Since the late 1960s, the consciousness of the consequences of unsustainable development has emerged. The American ecologist and biologist Garrett Hardin sowed the awareness for sustainable development, confirmed in article *Tragedy of the Commons* [1], that natural resources are finite and growing increase in population would bring serious effects on the natural environment.

In the aftermath, members of the Club of Rome released their concerns about the impacts of development on the environment in the book *The Limits to Growth* [2,3], in which it claimed that such a development was unsustainable. They reiterated that the accelerated exploitation of natural resources in order to support human activities, soon will collapse the environment.

Subsequently, the Commission for environment and development (*WCED*) warned of the dangers of unbridled development, which would bring irreversible damage to the planet and that they should be avoided to keep the resources for future generations. The WCED formulated a global agenda of changes which culminated in the *Brundtland* report [4]. This report described interests and challenges common to many industries in support of sustainable development.

In 1992, the United Nations Conference on environment and development (Eco-92) was held in Rio de Janeiro. This conference spread the idea of international cooperation to reduce poverty, seeking sustainable development and changing consumption patterns, through financing and transfer of environmental technologies. As a result, *Eco-92* produced *Agenda 21* [5], which brought a holistic view of the environmental sphere to cover the protection of rights: social, economic, political and cultural.

Two decades later, *Rio + 20*, the United Nations Conference on Sustainable Development was held in Rio de Janeiro [6], discussing the required strategies and measures. *Rio+20* produced the report *The future we want* [7], which reaffirmed the commitment of Nations with the themes discussed in *Eco-92*. All these discussions concluded that the development needs to be unlinked from the extensive use of natural resources, with the dematerialization of economies.

1.2 Strategies for the best use of resources

In dealing with natural resources, much has been done in the past two decades. In the years 1990s, the Organization for the United Nations Industrial Development (UNIDO) proposed to change strategies for cleaner production in the industry and, from this decade, emerged development concepts such as eco-sustainability tripod [8], ecological footprint [9] and green industry [10].

In the years 2000s the European Union has joined efforts for a better use of resources and waste management through the preparation of reports on *Thematic Strategy on the Sustainable Use of Natural Resources "* [11], the Raw Materials Initiative [12], and the report *Policies for sustainable use in the entire economy: management of natural resources* [13]. These reports presented guidelines for the best use of materials, waste management and the extension of the life cycle, which should be followed by European Union countries.

At the same time, Japan created the 3R strategy (reduce, reuse, recycle) and China created the circular economy law, which are policies such as strategies to reduce the consumption of resources by efficient use and recycling of waste [14].

In addition, groups in Austria, Germany and Switzerland began mapping work and production of database concerning materials and processes, documenting processes of extraction, production, market and transport; considering incoming and outgoing materials, substances and energy and calculating impacts with various sustainability indicators [15].

In Brazil, the *Brazilian solid waste Policy - PNRS* [16] was established in 2010 to promote more sustainable consumption habits, reverse logistics and waste recycling of packaging. The resolution No. 307/2002 of the national environmental Council (CONAMA) [17] and its updates established guidelines, criteria and procedures for the management of construction waste. Furthermore, the recent performance standards NBR

15575 series [18,19] seek to increase the performance and the life of the residential buildings and, consequently, reducing material consumption and generation of construction and demolition waste.

Beyond that, the *National Industrial Symbiosis Program (NISP Brazil)* seeks to increase profits and reduce risks of materials by the efficiency of resource use and waste exchange in the following regions of Brazil: Minas Gerais (agribusiness), Rio Grande do Sul (metal, post-harvest, furniture, stones, jewelry, fashion and textile) and Rio de Janeiro (waste database) [20–24].

1.3 Natural resources and civil construction in Brazil

Although Brazil has many natural resources reserves, this country is an exporting of primary materials and must plan carefully and efficient exploitation in order to avoid depleting its resources. A lot of natural resources and energy are extracted to meet the housing sector demand.

The extractive sector represented 4% of national GDP in 2013 [25]. The industry represented, in 2014, 24% of the national GDP and the construction sector represents 6.6% of the industry's GDP. On the other hand the construction and demolition waste generated in 2014 were around 44,625 (t * 1000/day), with an increase of 4.1% over the previous year [25].

A lot of the material extracted from the natural environment is used for construction. The minerals used in construction are abundant in Nature, on the other hand the excessive extraction can generate serious environmental impacts. As well as, transportation over long distances damages the environment by polluting gas emissions resulting from the burning of fossil fuels [26].

Transportation is an especially important factor in Brazil, where 58% of shipping materials is achieved on an extensive but underperforming road network when compared to international standards [27]. Consequently, cargo transportation in Brazil has high potential of generation of polluting greenhouse gases (GHG).

1.4 Justification

In Brazil, after two decades of construction industry crisis, this sector has significantly grown in the last decade [28], driven by funding programs for the construction and works to meet the various sectors related to the football World Cup in 2014 and the Olympic Games in 2016.

The growth acceleration program PAC-promoted social and urban infrastructure works (such as urbanization of precarious settlements, urban mobility, sanitation, tourist infrastructure) and financing for low-cost housing (as the *"Minha casa minha vida"* program) [29]. These programs have been promoting an increase in number of dwellings, stock of buildings and consequently, inert material in the buildings, which at the end of the life of the buildings will become waste.

The increase of material consumption and waste generation increases the environmental load of building stock by the direct impacts of extraction and production of materials and dumping of waste, but also by the transport of these materials during their life cycle. Besides, new construction systems were introduced in new buildings, such as plasterboard walls, and structural concrete brick walls, starting a process of change in the stock profile of buildings in Brazil.

Therefore, the justification of this study is given by the need to recognize of the building stock to control and improve waste management planning, and policy development for sustainability.

1.5 Goals, justification, scope and challenges

This thesis is concerned with the identification and analysis of the stock of residential buildings in Brazil and its dynamics regarding resource consumption, waste production, and life-cycle impacts from the waste flows.

1.5.1 Specific objectives

The specific objectives are:

- To review the events that led dematerialization of economies for the sustainable development;
- To conceptualize methods of Material Flow Analysis and Life Cycle Assessment;
- To analyze publications about MFA and MFA combined Cycle Assessment;
- To model typical residential buildings in Brazil;
- To estimate material intensity from the residential buildings;
- To estimate the stock of residential buildings;
- To estimate material and waste flows in the building stock;
- To model waste flows, considering the remaining time of the stock;
- To assess impacts relating to the waste flows and treatments of the most representatives materials.

1.5.2 *Scope*

The scope of the thesis is to provide an overview about the methodology of Material Flow Analysis, and to investigate material and waste flows and impacts from the waste flows, considering the remaining time of the stock and their demolition.

1.5.3 Challenges

The major challenges of this research are to overcome the lack of standardization of data and the complexity of the stock case study in the city of Rio de Janeiro, because of it is a big city, with great diversity in types of residential buildings. Moreover, the lack of inventory data in Brazil makes it difficult to analyze the impact of the life cycle.

1.6 Methods

1.6.1 Literature Review

In the Chapter 2, a literature review narrates the events surrounding the sustainability that motivated the development of MFA methodology; this Chapter presents concepts, applications, indicators and methods of MFA.

1.6.2 Bibliometric analysis

In Chapter 2, a bibliometric analysis on MFA is performed based on a search for articles in Scopus; we import the more "relevants" publications to the VOSviewer software and generate Maps of Networks from: repeated expressions, year of publication, authors, impact factor, and country of affiliation of the authors. These graphical representations allowed us analyze trends of publications of MFA.

1.6.3 Material Flow Analysis

The Material Flow Analysis (MFA) methodology assesses the balance and the flow of materials or substances across the border of a system. MFA has been applied, often combined with other methodologies, in different scales, objectives, and targets in different fields of expertise in support of sustainability. We create a new approach based in MFA and validate it in a case study of the residential building stock at Rio de Janeiro. Chapter 3 describes in detail the approach based on MFA used and presents a brief literature review on this methodology.

1.6.4 Life Cycle Assessment combined with Material Flow Analysis

Life Cycle Assessment (LCA) is a methodology for environmental analysis of products, materials, substances, or services. Under a perspective *"from cradle to grave"*, LCA analyses the entire chain of inputs, including the extraction of natural resources, manufacturing, assembly, use, dismantling, treatment at the end of life and distribution of material and waste. LCA are standardized procedures in the rules ISO14040 and ISO14044 [30,31], which suggest that LCA must be done in four steps: goal and scope definition, inventory analysis of life cycle impacts, and interpretation.

LCA has been used combined with MFA with many approaches and aiming to achieve different objectives. Chapter 2 presents concepts and discussions about this approach of MFA; Chapter 4 presents a brief literature review on this theme and uses these methodologies combined to analyze impacts of waste flows of residential building stock at the city of Rio de Janeiro.

1.6.5 Case studies from building types

Four hypothetical buildings, typical in Brazil, were modeled to determine the amount of materials in 1m^2 of total constructed area (TCA); TCA is the functional unit for estimation of material in the building stock. This case study is described in the Chapter 3.

1.7 Nomenclature

MFA	*Material Flow Analysis*
WCED	*World Commission on Environment and Development*
UNIDO	*United Nations Industrial Development Organization*
LCA	*Life Cycle Assessment*
NISP Brazil	*National Industrial Symbiosis Program*
PNRS	*Brazilian solid waste Policy*
GHG	*Greenhouse gases*

2 LITERATURE REVIEW AND BIBLIOMETRIC ANALYSIS FOR SUPPORTING THE SYSTEMATIC USE OF MATERIAL FLOW ANALYSIS

2.1 Introduction

Material Flow Analysis (MFA) was created during an advanced movement for the dematerialization and decarbonization of economies and systems for sustainable development. MFA is based on the law of mass conservation created by Lavoisier to evaluate the mass balance within and across the system border. MFA has been used to analyze the balance of materials, substances, land use (for human activities) and energy and quantifies materials stored in different scales systems in diverse fields of study.

MFA studies can deliver inventory of material stocks and analyze trends, aimed at preventing depletion of natural resources and the effects of environmental impacts. Thus, MFA serves the study of society's metabolism, which is the analysis paradigm for social interaction with nature through various subjects [32]. The adaptation of MFA for the application in different scales and economies deployed this methodology in several approaches and hybrids. This mix of approaches with numerous indicators of variations results in the overall understanding of MFA and consequently hinder their systematic application.

2.1.1 Motivation

International events to discuss the reduction and mitigation of impacts and preserving natural resources have led many nations to take a responsible attitude towards their growth and formalization of their commitment to sustainable development. In this context, MFA stands out among the methods for investigation, monitoring and analysis for increased performance and sustainability.

Studies of MFA cover various disciplines with different applications (such as global Anthroposphere, anthropogenic metabolism, countries or group of countries and industries or industrial parks), methods (such as MFA-Input Output, MFA-Economy Wide, Dynamic MFA- Economy Wide and MFA combined with Life Cycle Assessment) and approaches (top-down and bottom-up).

The use of socio-economic indicators broadens the scope of MFA studies from technical analysis to behavioral and market studies. On the other hand, the multidisciplinary approach in the use of MFA with blending methods and analyzing different scales and systems (or metabolism) tend to hinder the understanding and decision-making in developing the scope of work and the choice of the appropriate method for studies MFA.

A historical review gives an understanding of the rationale for the creation and development of MFA. A review of methods, applications, flow indicators and analysis of MFA studies allow a better understanding of the existing tools, and scopes and possible applications of this methodology. In addition, a bibliometric analysis gives broad idea of the dissemination of research in the scientific and academic community.

2.1.2 Objectives and purposes

The main objective of this study is to achieve a bibliographic review of MFA that shows the context of its creation and its development, clarifies definitions and compares approaches. Also, a bibliometric analysis of publications about MFA among keywords, clusters of repeated words, impact factors, authors and countries that highlight trends in publications. Therefore, this study aims to contextualize, explain, describe, and analyze the method and its publications to provide a broad understanding and promote the systematic application of MFA.

The secondary objectives of this study are:

- To identify important events and concepts related to sustainability;
- To discuss the influences and trends for sustainable development;
- To enroll studies and highlight policies that were based on Material Flow Analysis;
- To conceptualize Material Flow Analysis: methods, concepts, indicators and databases;
- To categorize approaches of Material Flow Analysis;
- To investigate recent publications about MFA, highlighting the most important ones;
- To make a critical analysis of the outcome.

A narrative review of the awareness of the society for sustainability, reviewing the literature of Material Flow Analysis while an analysis of bibliometric study aimed to give an overview on the subject and provide an understanding of the context and the MFA and its systematic application.

2.1.3 Bibliometric analysis

Bibliometric studies have been used to consolidate literature review studies as *State of art* through analysis of trends publications about specific topics in the chronological distribution analysis, countries, institutions, titles, categories and keywords [33,34]. We present a bibliometric study that gives an overview of the issue of development in terms of academic publications.

2.2 Materials and methods

- The literature review of the background for MFA presented and discussed the events that culminated in the creation of this methodology, and the purpose for which it was created are presented and discussed, as well as, presents policies and strategies bases on MFA and a timeline of main events related to awareness for sustainability;
- The literature review of the MFA contextualizes, conceptualizes and discusses its applications, indicators, methods, studies sustainability strategies, databases and software;
- The Bibliometric analysis is made based on a search for keywords about MFA in Scopus database, considering aplications, methods and concepts, in the subjects of Engineering and Environmental Science. We import the 2000 more “relevants” publications, according the Scopus’ classification, to the VOSviewer software and generate Maps of Networks from: repeated expressions, year of publication, authors, impact factor, and country of affiliation of the authors. These graphical representations allowed us analyze trends of publications of MFA;
- The bibliometric analysis survey MFA publications in the Scopus [35], presenting bubble graphics were made with the tool VOSviewer [36]. Besides, the main recent

publications about MFA with Latin American and Brazilian participation found in Scopus, are described;

- Based on literature review and bibliometric analysis, we complete a critical analysis of the results.

2.3 Literature Review: Background

2.3.1 Awareness for sustainability: historical narrative

The awareness for the necessity of sustainable development is based on perception of climate scientists, which would be the result of environmental imbalance by exaggerated exploitation of the environment. After long discussions between governments and scientists and deep scientific studies such climate changes, and the investigation of its effects and causes were proven. The scientists concluded that, if the exploitation of the environment is not drastically reduced, the planet will collapse soon [4,37,38].

Since the late 1960s scientists have discussed the consequences of human intervention in the environment. Societies are becoming aware and have been creating standards and tools in order to control the damage that disrupt the environment.

From then on, new hits of sustainability concepts, among them we highlight the sustainability triangle, which was developed based on the three aspects of sustainability, and the concept of cleaner production. In 1990, John Elkington introduced the concepts of the sustainability triangle (triple bottom line), which were the social, ecological and economic aspects as bases for a sustainable development [8]. This concept was adopted by the United Nations and is widely used to represent the components of sustainable development. Sachs [39] addressed five aspects as the basis of sustainable development and offers reflections on the five dimensions of sustainability: economic, social, ecological, geographic (or spatial) and cultural. In general terms, this author argued that social sustainability depends on greater equity in the distribution of incomes and property, with less social differences and economic sustainability should take into account not only economic aspects, but also "macro social" aspects. In the years 1990, the Organization for the United Nations Industrial Development (UNIDO) and the United Nations

Environment Program (UNEP) created the concept of cleaner production [10]. The cleaner production requires a change of strategy processes, products and preventive services to increase the eco efficiency and to reduce risks to health and the environment. This includes reducing consumption of natural resources and energy, as well as the prevention, reduction and reuse or proper disposal of wastes and tailings production. Even today, UNIDO´s reports of Green industry support policies for sustainability.

2.3.2 Dematerialization and decarburization of economies

In a global context, there is a consensus that for development to reach a higher degree of sustainability from development, we should reduce "environmental pressures" improving its environmental performance, an efficiency in production, use and management of materials [40] and best decisions about treatment and management of resources.

The perception of a link between development and scarcity of resources and environmental pollution promote deep analyzes of economies to avoid the scarcity of natural resources, mitigate and prevent pollution and reduce the amount of waste generation and its toxicity, and the resulting environmental impacts. Thus, productions for goods and services and logistics for production and distribution should be more efficient: increasing the shelf life of the products, and encouraging recycling and reuse of materials. Therefore, companies must be well informed to require more sustainable products. On the other hand, governments create goals for sustainability, involving industry and society in the transformation process of development, minimizing pressures on the environment. Governments seek to:

- Create policies for reducing resource consumption and waste generation (pollutants and inert materials);
- Encourage scientific research to solve problems relating to pollution (such as reverse greenhouse effect, for example);
- Promote industry interest by creating new technologies for more sustainable products, with cleaner production;
- Promote production optimization and minimization of transregional offsets [41];
- Encourage the society to make their consumption patterns more sustainable.

Thus, Governments require that industries and companies to assume their responsibility for the pollution they produce. In addition, governments seek to overcome the environmental and socio-economic requirements, and also regulatory restrictions to develop resource management policies that are oriented to a sustainable economy [41].

In practical terms, the insufficient reserves of resources for production of material (greater demand than production) and expenses resulting from the importation of materials (market value) and impact mitigation increase industry cooperation for sustainable development. The industries shall get the efficiency throughout the production of supplies of services in order to reduce the consumption of raw materials and perform a clean production. To this end, the industry needs to create and update standards of products, production processes, logistics, waste treatment, in summary, all services to which they are responsible.

Societies which today still focus on the well-being and the lowest economic cost in detriment to the environmental cost, should contribute changing their patterns of consumption: requiring products of higher quality and durability [42,43] and separating the waste generated by type of material. Minimizing the generation of waste and facilitating the recycling of waste.

However, the mechanics for efficient production becomes unenforceable in societies of great economic inequality, which often come accompanied by low levels of industrialization and urbanization. The economic inequality segregates these societies by levels of income and human development index. Therefore, only a part of the population is engaged to have conscious consumption, while the majority of it survives under inadequate sanitary infrastructure, urbanization, and has no insight for better consumption choices and neither has financial conditions to acquire technical assistance in sectors such as construction. Some industries are established with low levels of investment for deployment, equipment and manpower, and without concern to have performance or to avoid environmental impacts. In such conditions, public policies are of low efficiency, because it does not cover the large portions of sectors working freely informal or even illegal. Therefore, these companies will have the challenge of combating social inequality, the disarray in industry, urbanization and the awareness of the population to achieve the dematerialization and sustainability comprehensively and effectively.

Societies and industries exert great pressure on the natural environment due to the lifestyle of exacerbated consumption and industrial production on a large scale. Aiming to achieve sustainable development, government is creating strategies to dematerialisation, for reduction in the transport of materials, lightening impacts and reduction of social inequality. These strategies should encourage the industry to reduce waste and encourage people to acquire more conscious consumption patterns (Fig. 2.1).

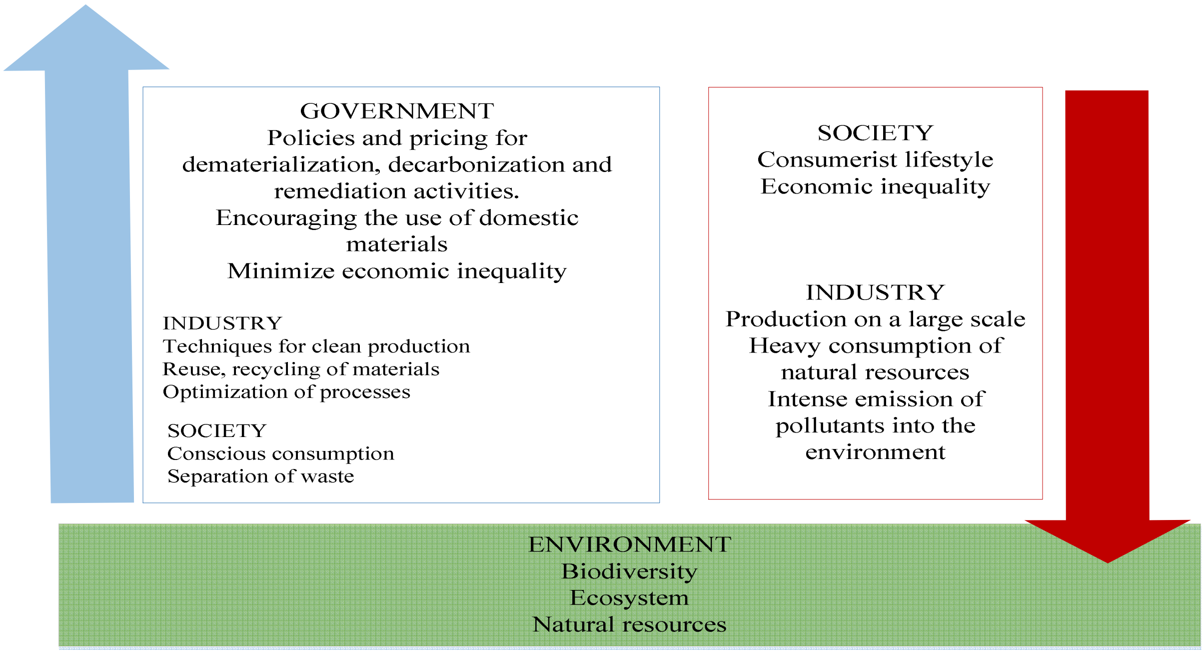

Fig. 2.1 - Society influence on the natural environment.

The analysis of current levels of industrialization and development and trends of resource usage determine the possible ways of reducing consumption and environmental impacts in the future [44]. So it is important to consider the dynamics of urbanization, industrialization and income levels, economic inequality and urban planning in the region to have a broad vision of the material balance and possible optimization of productive chains of a region.

Therefore, government and society must work together to encourage the industries to seek affordable technologies and logistics of cleaner production through public policies and societal pressure for higher quality and durability. Resource consumption trends point towards the decoupling of economic growth with the consumption of natural resources (dematerialization) and waste emission pollutants to the environment, especially the polluting gases (decarbonizing).

Methods for inventory and analysis were created as tools for mitigation and prevention of pollution and, later, for optimization of systems. In the inventory surveys the inputs, outputs, stocks and flows of matter and energy that cross the boundaries of systems to help to identify points of weakness and robustness of systems; this type of study results extremely complicated, expensive and laborious. In the case of an economy, the stock of materials are comprises buildings, infrastructures and durable goods. In studies for system optimization, different scenarios are analyzed in sustainability aspects to identify the most advantageous option.

Table 2.1 shows several important strategies, policies and studies that were based on the methodology of MFA, your country or institution of origin, your goals and the aspects considered. Therefore, MFA was the basis for the development of environmental protection policies, such as the "thematic strategy on the sustainable use of natural resources" of 2005 (European Union-EU), "Strategy for sustainable management of materials" of 2004 (the OECD), "Japanese Strategy" 3Rs (reduce, reuse, recycle) of 2005, "China's law on the Circular Economy" in 2008 and "Korea's green growth policy for the sustainable development of a low-carbon society" [14,45]. These strategies seek to research knowledge of processes with high rates of waste, which must be improved for better raw material conservation.

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Table 2.1 - Strategies, policies and studies based on MFA, part 1; Acronyms: EC- Economic / TS- Trade & supply / T-Technology / NR-MP- Natural resource management policies / P-IP- Identify and prevent pollution / M&W-I- Identify waste of material and seek efficiency

Policies, strategies or studies, and agent	Aspects	Goal
3R Strategy (2005), Japan [14,46,47]	EC/TS/T/ NR-MP/P-IP/M&W-I	Proposed national guidelines and local plans for management of all types of waste and promoting recycling. Such a strategy has also been applied to Asian countries: Bangladesh, Indonesia, Vietnam, Cambodia, Philippines, and Thailand.
Studies, Japan [45]	TS	Study the world resource flows around Japan (e.g. aluminum flows and associated CO_2 emissions)
	TS	Useful tools
	TS	Economy-wide MFA with an appropriate coverage of trade flows by origin and destination
	TS	Environmental input-output analysis
	TS	International input-output tables
	TS	Hybrid approaches combining physical and monetary analysis
	TS	International trade statistics
	EC	Use of material flow accounts to calculate national resource productivity indicators in support of the Government's Fundamental Plan for establishing a sound material cycle society
	T	Use of MFA in the automobile industry (Toyota Motor Corporation)
	M&W-I	Use of material flow accounts to calculate waste and recycling indicators in support of the Government's Fundamental Plan for establishing a sound material cycle society
Circular economy (2008), China [48–50]	EC/TS/T/NR-MP/P-IP/M&W-I	Laws to facilitate the circular economy, raising the utilization rate of resources, protection and improvement of the environment and achievement of sustainable development
-Green growth policy for the sustainable development of a low carbon society, Korea -The National Strategy for Green Growth (2009-2050), Korea -The Five-Year Plan (2009-2013), Korea [14]	EC	Promote new eco-friendly growth engines, improve the quality of life of people and contribute to international efforts to combat climate change.
Study, Australia [51]	NR-MP	Accounting for water resources to support negotiations on water allocation.
WRI study (1992), USA [45,52]	EC	Guidelines for Action to Save, Study, and Use Earth's Biotic Wealth Sustainably and Equitably
Studies, USA [45]	P-IP	Study of heavy metals and other hazardous substances in the New York/New Jersey harbour United States: mapping of nitrogen flows in the Mississippi Basin (USGS) Study on chlorine flows (research project, Yale University)

	NR-MP	Studies of world metal flows (copper, zinc, silver, nickel, etc.) by the Yale University, Stock and Flows project
		Economy-wide MFA with detailed breakdown of materials for input and output flows
		Substance flow analysis
		Life cycle analysis of products
		Waste statistics and accounts
		Material system analysis and material specific flow accounts

Table 2.1 - Strategies, policies and studies based on MFA, part 2. Acronyms: EC- Economic / TS- Trade & supply / T-Technology / NR-MP- Natural resource management policies / P-IP- Identify and prevent pollution / M&W-I- Identify waste of material and seek efficiency

Policies, strategies or studies, and agent	Aspects	Goal
Mass Balance Biffaward program (2004), UK [51]	EC/T/M&W-I	Study by the business sector on iron, steel and aluminum and other
Mosus project, SERI, EU [53,54]	EC	Macroeconomic, multi-sectoral framework three major themes of European policies: sustainable development, competitiveness and social cohesion in the knowledge-based society, and Globalization and international trade.
Raw material productivity (2008), DE [55]	EC	Housing, cooper, steel
Research study on indirect material flows associated with imports (2004), Italy [56]	EC	Economy-wide material flow indicators time series for Italy and Italian Physical Input Output Table feasibility study
Strategy of sustainable materials management SMM (2004), OECD [57]	M&W-I	Policies that give recommendation and instruments for promoting SMM, and for contributing to implementation of the OECD Council Recommendation on Resource Productivity adopted in 2008
Studies, OECD [45]	T	Useful tools Useful tools Material system analysis and resource specific material flow accounts Life cycle analysis of products Value chain analysis Value chain analysis
	NR-MP	Material system analysis and resource specific material flow accounts Natural resource accounts: asset and flow accounts
Studies, Sweden [45]	P-IP	Study of mercury, lead and copper flows in the Stockholm area Study on chemical products in industry
Study, Denmark [45]	P-IP	Mass flow analyses of mercury
Study, Austria [45]	M&W-I	Use of material balances and lifecycle analysis to determine the effects of product re-use on resource conservation (applied to electrical and electronic household appliances)
Study, Norway [45]	M&W-I	Waste accounts

In addition, since 2005, the European Union environmental and economic policies to promote efficiency in the use of resources, such as *Thematic Strategy for the Sustainable Use of Natural Resources* (2005), *Resource Efficiency Flagship Initiative* (2011) and *Roadmap to a Resource Efficient Europe* (2011) [58].

Furthermore, the Rio+20, the United Nations Conference on sustainable development, was held in 2012 in Rio de Janeiro [6]. One of the challenges for Rio+20 were highlights in the search of combining economic growth, employment generation and poverty reduction with environmental sustainability [59]. The production of the Rio+20 was the document *The future we want* [7], which reaffirms the commitment of Nations with the topics discussed, but we had few practical results and no new proposals were presented. The biggest advantage of Rio+20 was to mobilize the world's civil society who performed several side events at the United Nations Conference on the sustainable development debate.

Recently, representatives of dozens of Nations signed agreement in the climate summit of Paris by 2015, a global extension agreement (COP21) [60] to reduce emissions of greenhouse gases and to minimize the impacts of climate change. In this agreement, 195 countries commit to act in order to keep the temperature rise to only 1.5° C, instead of 2° C as predicted for 2020, with the goal of gradual reduction until emissions zeroed until shortly after 2050. Promising to carry out public-private partnerships in the area of clean technology innovation, solar energy and carbon pricing to fight global warming [61], where poor countries will be funded by the rich countries.

Therefore, the idea of sustainable development had as starting point the awareness for the necessity of preserving the environment for future generations, in the Decade of 1960. Next, extensive researches and numerous debates in search of causes and potential consequences of the scarcity of natural resources, global warming and climate change; which emerge in concepts of ecological and sustainability.

In addition, hundreds of countries signed treaties of reciprocal agreements commitment with the deceleration of the causes of the ozone layer depletion. The midst of these events around the sustainability, the scientific community has concluded that sustainability can only be achieved through the untying of development of societies with the consumption of natural resources and energy. Thus, savings come seeking its dematerialization and decarburization by improving performance of processes involved in the life cycle of products and services. And in this context, MFA has developed various approaches as main methodology to achieve dematerialization in different scales of economy.

2.3.3 MFA: institutions, standardization and tools

2.3.3.1 Institutions

In 1981, the World Resources Institute (WRI) was founded in the United States (US). Since then, MFA (by weight indicators and per person) has been used in several areas to aid State planning. [14].

In 1991 the Wuppertal Institute in Germany has been set up to study climate, environment and energy [41]. This Institute was created to research and develop concepts, strategies and tools for transition to sustainable development at regional, national and international level. So, the Institute investigates the interaction of climate, resources and energy with economy and society. Since then, the Institute Wuppertal has been developing MFA methodology applied to the economy, with the focus on the investigation of material flows throughout the life cycle [41].

This Institute joined the National Institute for Environmental Studies (NIES) of Japan and the Institute of Social Ecology (SEC) in Austria to create a conceptual and methodological pattern between Japan and Europe in the investigation of the interaction of climate, resources and energy to economies and societies. Both the WRI as the Wuppertal Institute have direct participation in use of MFA and the creation of databases of material flows.

2.3.3.2 Description and standardization of MFA:

In 2001, the European Commission (EUROSTAT) has published a methodological guide to describe and standardize the methodology of MFA [62]. This guide has received updates and, even today, is considered a reference guide on MFA among researchers.

In 2002 Ayres R and Ayres LW published the book *the Handbook of Industrial Ecology* that conceptualizes the field of industrial ecology as the study area of sustainable development. This book indicates not only the industries, their product designs and manufacturing processes, but also, the consumerist tendencies of society as a cause of instability. The mass consumption of society requires the deployment of large-scale production technologies and consume many resources that the environment is not able to recover. So, in the Ecology Industrial field, scientists and the like investigate the entering, exiting and internal flows of material and energy to the ecosystem and analyze the behavior of industry and consumption trends of society [63].

In the years 1990s, Brunner and Rechberger developed the concept of Material flow analysis (MFA) and published in 2003, *The practical handbook of material flow analysis* [64]. In this manual, the methodology of the MFA is set and some case studies are presented to help understand its implementation.

In 2005 the World Resources Institute [65] published a report of material flow accounting models, the theme definitions and specifications of materials included in the database of the United States [66]

Bringezu published in 2006, the document "Policies for sustainable use in the entire economy: management of natural resources" which discusses about waste management approaches in the context of the European Union [13].

In 2007 the International Panel for Sustainable resource management established by the United Nations Environment Program (UNEP) held a world scientific meeting in Budapest to discuss the environmental effects of the consumption of renewable and non-renewable resources. Since then annual meetings are held to debate the theme [67].

In 2008, the Organization for Economic Cooperation and development (OECD) has published the report "Measuring the material flows and resource productivity" [45,68]. This document reflects the State of the art experience of the material flow analysis by that time and the related indicators in member countries.

In the years 2000s the European Union published reports for the sustainability of natural resources. The reports "Thematic Strategy on the Sustainable Use of Natural Resources" [11], the EU Raw Materials Initiative [12] present guidelines for better use of materials and the extension of their life cycle, which should be followed by European Union countries.

Also in 2000, the OECD [69] published a methodological guide for material flow accounting for the entire economy and derived indicators.

In 2009, the Organization for economic co-operation and development (OECD) and the United Nations Environment Program (UNEP) presented at the workshop the study "sustainable management of resources and materials-Linking national and international initiatives" in Copenhagen. In this workshop, partakers discussed the general framework for MFA. Several countries have joined together in an efforts to create policies for economic decision-making in the interests of sustainability, such as put a price on carbon.

Also in 2009, Reisinger and Finocchiaro [70] published an executive summary for the use of MFA for policies in buildings waste management that presented methods and indicators.

The UNEP has published, in 2011, the report *Decoupling Resource Use and Environmental Impacts Natural from Economic Growth* that conceptualizes, discusses and brings special cases about the dissociation of natural resources and the environmental impacts to economic growth [71].

Sonnemann, in the ACL Conference avniR [72] held in France in 2012, cited some economic accounting offices that are data sources for PIOT studies such as: BEA-Bureau of economic analysis in US [73], central Bureau of statistics of the Netherlands [74], Federal Statistical Office of Germany [75], assessing economic performance data in national areas, regional, international and industry and provide data, and the OECD, working with statistical data from several countries.

2.3.3.3 Data base and software

Many countries have fueled the database with natural resources life cycle, emissions to air, water and soil data, which allows the estimation of environmental intervention and overview of this intervention in an economy.

The WRI has been developing a database of materials flow through the economy of the United States including data on Carbon emissions and electricity in many countries. This database makes the compilation and periodic disclosure of information to civil society and covers the physical resources of 190 products entering into the economy and monitor their movements and transformations through the life cycle of the material [65].

The European Sustainable Research Institute – SERI [76] in co-operation with the Wuppertal Institute compiled a database that covers extraction data, market and consumption of 12 categories of materials in more than 200 countries, in the period between 1980 and 2008 [77].

The Eurostat has produced a database of material flows to European economies in categories of materials, such as fossil fuels, biomass and metal ores [78] and been feeding your database with data from its member countries.

The *Comprehensive Environmental Data Archive* (CEDA) is a database created in the United States that covers various environmental systems analysis (including carbon footprint, water footprint and embodied energy) and life-cycle analysis [79]. The US has partnered with the European Commission for the creation of environmental policies and with the *Sichuan University* for the preparation of the inventory database of Chinese life cycle.

CSIRO and UNEP offer a database of MFA of Asia-Pacific region [80] in order to promote understanding of the growth of the countries of the region regarding the consumption of natural resources, assess the impact of policies adopted.

The *European reference Life Cycle Database* (ELCD) [81] was created in 2006 is a database with life-cycle inventories in Europe. The data is provided by business associations and other sources of essential materials, energy agencies, transport and waste management.

EcoInvent [82] is an international life cycle database prepared by the *Ecoinvent Centre*, in Switzerland. *EcoInvent Centre* is regarded as the most complete database and is included in major LCA tools. *Ecoinvent Centre* created a tool kit to facilitate the submission of inventories by customers. Besides, LCA software as *Simapro* [83], Gabi [84] and *OpenLCA* [85] also have their own database.

STAN and UMBERTO are software used for producing MFA´s tables, charts and Sankey diagrams. STAN [86] is a software developed according to Austrian standards of *Material flow analysis-Application in waste management* and is used in MFA studies-SFA [86–88]. The Institute for Social Ecology, Vienna, Austria [56], provides databases of SFA and publications on the subject. This Institute investigates aspects of society-nature interactions, such as metabolism, land use, environmental and social information and the systems of indicators of sustainable development. UMBERTO [89] is a commercial software to life-cycle assessment, analysis and process optimization, support for integrated action between environmental efficiency and cost and carbon footprint analysis. UMBERTO works with the databases from *EcoInvent Centre* and *Gabi*.

2.4 Literature Review: Material Flow Analysis

Material Flow analysis (MFA), also known as *Mass balance*, *Material Flow Accounting* (when by economic approach), or *Substance Flow Analysis*, is a methodology for analysis of stock and flows of matter, substances, energy and land use within a system in a set time [64].

MFA emerged in order to assess and analyze systems for sustainable development, and can be used in various scenarios in different type and scale.

Studies of mass balance follows the precept of the first law of thermodynamics, the law of conservation of matter, which states that matter is not created or destroyed by any physical process [45]. Thus, the resources used by humans prior to the natural environment, are transformed, can get serving some function (stock in use), are dismantled and sooner or later are released into nature as waste.

MFA has been applied in the analysis of mass flows, substance and energy. In MFA, *stock* material reservation within the system, being the *"goods"*, intangible assets as energy, information and services, and the "*processes"*, the actions such as processing, transportation and storage.

The main target of MFA is to promote better decision making in resource and waste management planning. However, MFA can be applied at different scales and boundaries, and may serve many purposes depending on the specific scope stipulated, including, when combined with evaluation of life-cycle impacts, environmental management and numerous other methodologies for product optimization.

MFA has been applied widely to sustainable development in the aspects of optimization of production processes and logistics industries, analysis and prevention of environmental pollution by industrial and/or human occupation. It is also used in the creation of policies for environmental cleanup, pollution mitigation and sustainable development [64].

The application of MFA produces the survey data of the material flow system, identifies stocks and the mass balance across the boundary of the system, monitoring the accumulation or depletion of stocks. A better planning of management of materials, substances, energy takes place in the modeled scenario analysis, highlighting changes that can make more efficient systems and damages to be mitigated. Therefore, MFA contributes in subsidizing better decision-making in planning for reduction of environmental loads in the future, for the preparation of projects, efficient products for process creation and environmentally beneficial systems [90].

Physical and/or socioeconomic data are requirements for MFA inventory systems as the entries of biotic and abiotic resources, water and air consumption, solid waste outputs, wastewater, gaseous emissions and stagnant stock. The system can investigate its process in detail or can be considered a "black box", considering only material, substance and/or energy who exceed the borders of the system and ignoring the processes and sub-processes that occurred within the system [77,91].

To improve the comparison of scenarios, indicators such as Material Intensity Per Service (MIPS), Material Intensity (MI), Ecological Rucksack, indicators of market balance and socioeconomic indicators are included in MFA studies. Concerning the approaches of calculation, *bottom-up* (incrementally) or *top-down* (in decreasing order) can be used [92–94].

The *bottom-up* approach makes incremental estimates, review cases with physical indicators, and extrapolates the results to meet larger scales. While the *top-down* works with statistical data and socio-economic indicators, usually applied to economies of countries or groups of countries. The literature review shows that MFA has been applied to the global Anthroposphere, urban metabolism (of country or group of countries, region, city or neighborhood), and industries or industrial parks. Among the methods of MFA, the mass balance (or MFA of inputs and outputs), *Material and Energy Flow Analysis* (MEFA), *Material Flow Accounting* throughout the economy (MFA-EW), *Material Flow Accounting Dynamic* and *Material Flow Analysis* combined with *Life Cycle Assessment* (MFA-LCA) stand out.

2.4.1 Applications

2.4.1.1 Global Anthroposphere

MFA applied to global Anthroposphere aims to investigate material flows, by the market interrelation between countries and continent. This application maps and models globally flows between countries, the activities, structures and the interdependence of these aspects and regions [64] [95]. Fig. 2.2 shows the conceptual model of the MFA applied to the anthropogenic environment. In this application, consider the flows between various economies, extractions of resources, polluting emissions and waste generation (in the lithosphere, the hydrosphere and the atmosphere).

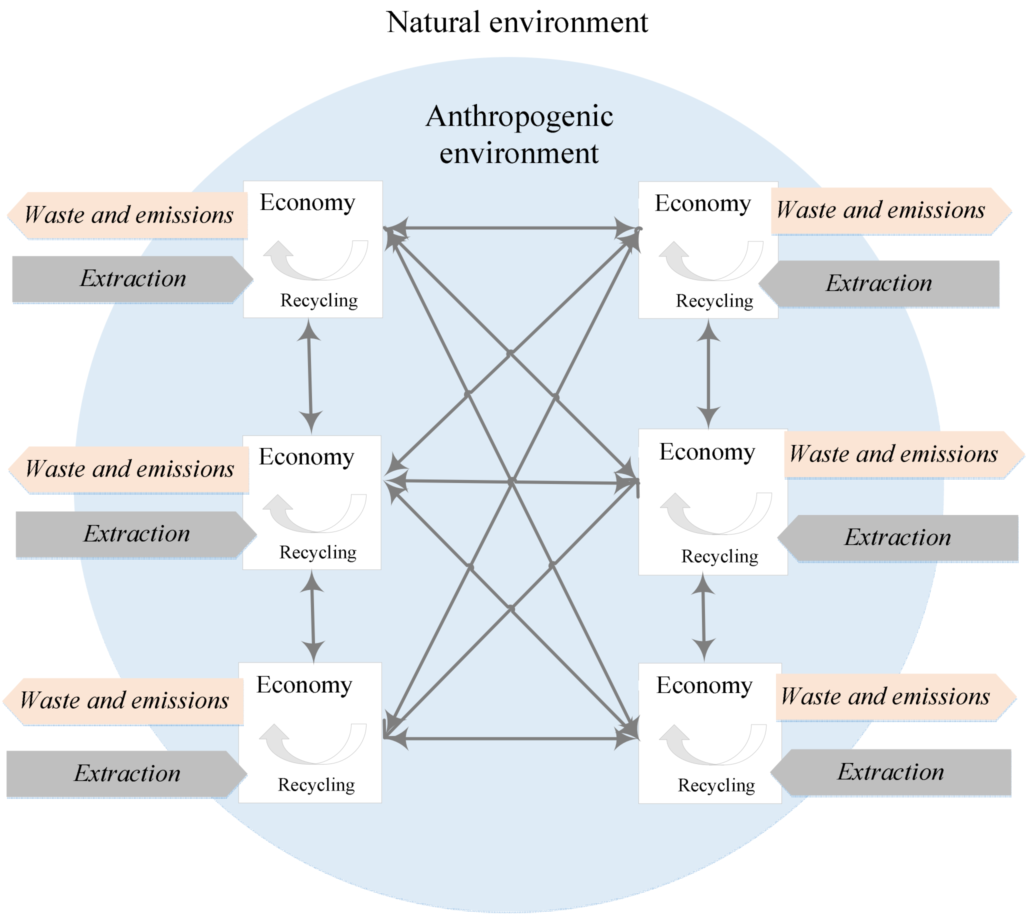

Fig. 2.2 - Conceptual model of MFA applied to the anthropogenic environment

The study of Liu and Müller [96] An example of this application, in which the flows of bauxite, alumina, aluminum, semi-products, products and scrap were mapped. The authors consider several stages of transformation of material cycle and identify trends in production, consumption and market.

Through this application we can collect data from exploitation and pollution that allow us to anticipate criticism about depletion of natural resources and predict when effects of pollution will reach intolerable levels to man highlighting the unsustainable development. Moreover, from that, we can create strategies to mitigate the effects of exploitation and pollution already committed and to prevent depletion and pollution in the future; restoring the balance between the environment and development of human occupation.

2.4.1.2 Anthropogenic and Anthroposphere Metabolisms

MFA applied to anthropogenic metabolism aims to plan for sustainable development through the rational use of natural resources. MFA applied to Anthroposphere analyzes the main flows of material and energy required by the land use to meet the human metabolism [97], as well as the emissions of waste dumped on the ground, in the water and in the air. However, its application to a global scale is inaccurate for their breadth and complexity and remains conceptual. In practice, the analysis of anthropogenic metabolism occurs in smaller countries geographical stalls, cities or regions.

2.4.1.3 Urban metabolism of countries, groups of countries and regions

Urban metabolism studies in countries or groups of countries (like the United Kingdom, for example) focus on the flows of materials and energy, assessing the main flows of material and energy required by the land use to meet the Urban Metabolism of a city or region, specifically their infrastructure.

Figure 2.3 shows the conceptual model of the MFA applied to countries or groups of countries and regions. In this application, the system is the anthropogenic environment within the geographical border, which extracts resources from the environment, move resources (natural and manufactured) by importing and exporting and dumping emissions and waste in the environment, which can indirectly affect the entire planet. The application of recycling enables the use of resources in looping, increasing the service life of materials and reducing the environmental stress levels.

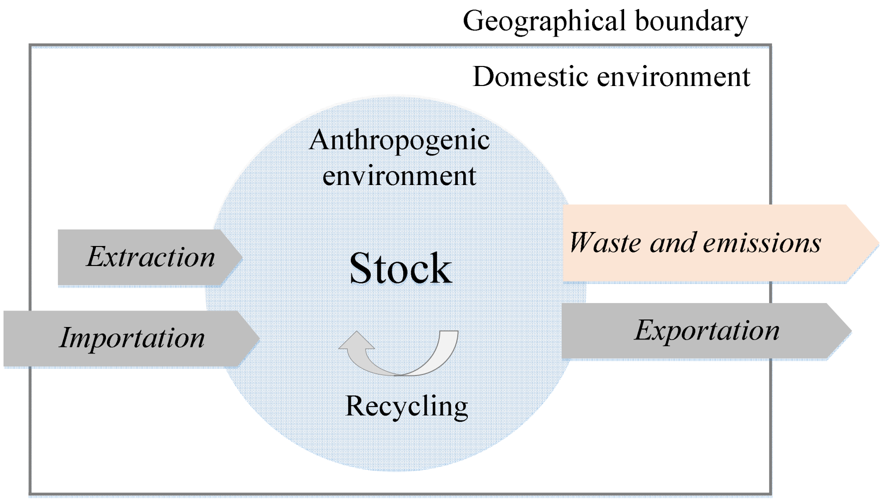

Fig. 2.3 - Conceptual model of MFA applied to an economy

This application of MFA analyzes regional materials or swings a single material system [70,90] and, commonly, analyzes consumer trends. However, the bibliography presents studies that analyze multiple material flows through repetition of calculations [91]. As a result, this application of MFA presents the inventory of inputs, outputs and stock of materials and energy and, often, material consumption forecasts. MFA studies with this application have been helping the development of sustainable policies.

The application of MFA across the economy should consider local characteristics and requires extensive knowledge of physical data, and material consumption of industry. The difficulty in obtaining these data promoted the creation of *MFA-Economy Wide*, which accounts for domestic consumption of materials and materials stored in the system from market economic data for import and export. So often it uses economic indicators or economic indicators combined with socioeconomic ones as inputs in the study, in top-down approaches.

2.4.1.4 Urban metabolism of city or neighborhood

The urban Metabolism studies the causes and effects of resource depletion and environmental issues, through the analysis of flows of goods such as fuel, building materials, food, water, waste, sewage, and emissions. Many of the MFA studies applied to a city or neighborhood focus on inventory of stagnant material in buildings, energy consumed by them or in waste generated. This type of MFA application promotes better management of resources and waste and higher efficiency of materials and energy sector.

In order to find the demand of the city, sometimes materials from outside its borders that are related to local consumption of energy are used. In this case, material and energy are accounted by MEFA (Material and Energy Flow Analysis) method [98], or by inventory of physical indicators of consumption or of waste generation. Being calculated under bottom-up methods applied to specific sectors, such as, the consumptions by stock of buildings [99]. This application requires many market data. The difficulty in obtaining these data is an obstacle to the use of this approach.

Fig. 2.4 shows a representation of the urban metabolism. Where the system is composed of the stock, their internal activities and the addition in stock; the inputs are local extraction, local import, import of other countries; and outputs are: waste disposal in sites, regional export, export to other countries and the generation of waste and emissions.

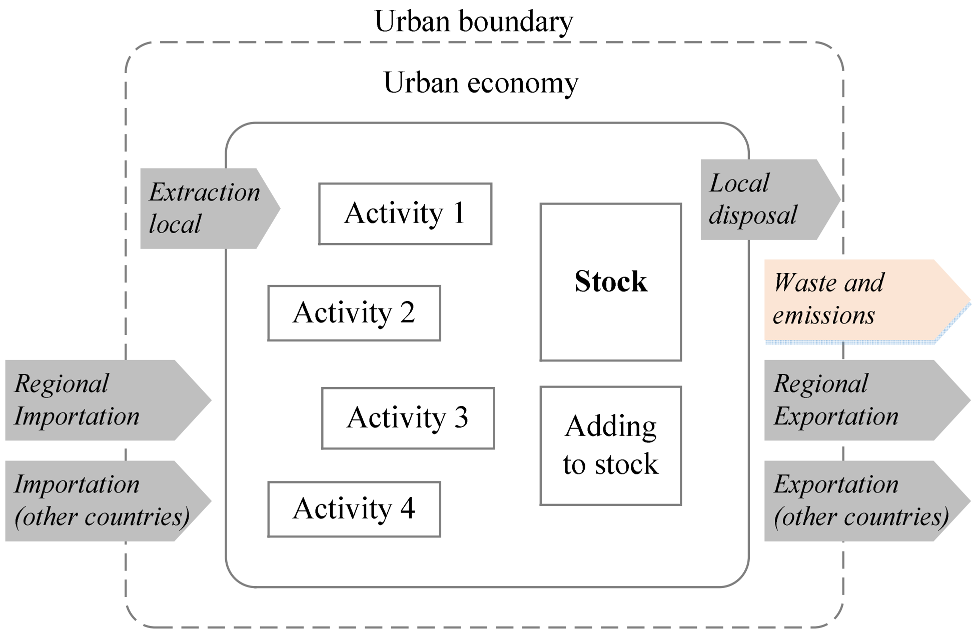

Fig. 2.4 – Schematic representation of urban metabolism, based on (ADB, 2014)

Kennedy *et al.* [100] analyzed, based on a literature review, urban metabolism of eight metropolitan regions from five continents from 1965 until 1990. They evaluated the variations in a stock of buildings, consumption and all dumps and human occupation and its impact (changing water levels, soil depletion of local materials, accumulation of toxic materials, islands of summer heat, and irregular buildup of nutrients). The increase per capita in consumption of energy and material and as well, waste water generation had gradual increase constants. While atmospheric emissions and solid wastes have had changeable dynamics.

Zhang [101] presented a literature review of urban metabolism presenting a conceptual representation for inventories, analysis and optimization of urban metabolism. According to Zhang, the study was conducted in four parts: process analysis, accounting and valuation of stocks and flows, simulation of dynamic models and practical application.

The process analysis evaluates linear, cyclic and chain processes by accounting and evaluation of flows, stocks, and energy intensity in order to measure the efficiency of metabolism. In the review, the weaknesses of the system can and should be improved. In the simulation of dynamic models, different scenarios are tested in different ecological models, mechanisms of influence and models of inputs and outputs. First, the existing system is modeled, and later the system is re modeled with some modifications aimed at achieving greater efficiency scenario. In the practical application, the metabolism was optimized and regulated in function of nodes, paths and streams, and regulations are created to apply the best scenario.

Although this concept has been presented to the urban metabolism, it has been the basis for many systems optimization studies conducted by MFA or Life Cycle Assessment (LCA).

2.4.1.5 Industry or industrial park

Also known as Industrial Ecology, MFA applied to industrial sector aims to optimize production and the routes of uses and processes [64]. MFA examines the industrial input and output balance for natural ecosystems and seeks to control the use of materials and industrial processes through closed-loop, practices to increase efficiency in the production with:

- Energy and waste self-sufficiency (with replanting of vegetation and carbon sequestration in the form of energy (ARNOLFO, 2013));
- Dematerialization of the industrial production (getting more goods and services from a smaller quantity of matter and make the product more durable [102]);
- Systematization of energy usage patterns [90];
- Analysis of the balance between inputs and outputs of the sector and the capacity of natural ecosystems resilience [90].

MFA is applied to all stages of the production in an industry: extracting of resources of its natural origin, obtaining of supplies, the manufacturing products and distributing to final customers. The inventory under the approach *bottom-up* allows the promotion of practices for production and logistics optimization, increasing efficiency and promoting dematerialization of production.

Among the methods used for industries, the literature presents MFA, *Substance Flow Analysis* (SFA), *Input-Output Analysis* (IO) and *Life Cycle Assessment* (LCA).

Fig. 2.5 shows a conceptual representation of the modeling of systems that shows the flows of materials with the extration of resources from the natural environment, the inputs and each process mass exits and dump emissions and waste in the natural environment (lithosphere, hydrosphere and atmosphere). Thus, the materials undergo transformation processes, use (when in stock), disablement and recycling. This modeling system is also applied to *Life Cycle Inventories* (LCI) on research inputs and service outputs and mainly products.

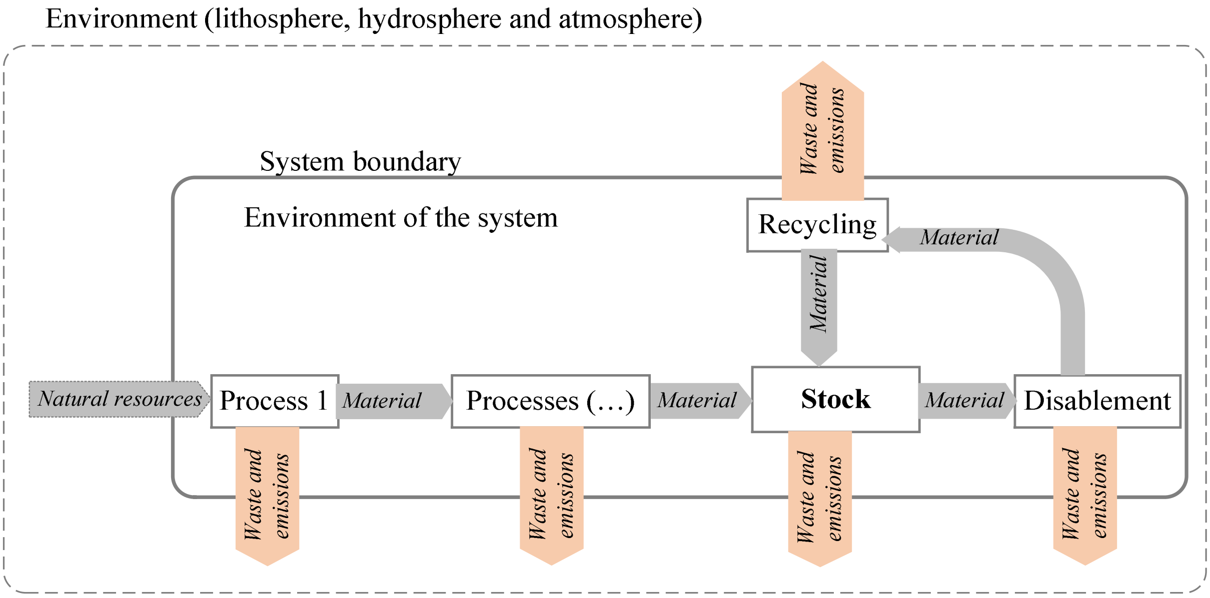

Fig. 2.5 - Conceptual representation of modeling systems

2.4.2 Flow indicators in MFA

Indicators of resource consumption and production of materials find out regional trends, and the ratio of efficiency in productivity. This indicators can reduce the uncertainty in the inventory input and output material in the system and between it and the environment. Among numerous resources and production indicators, the most used in MFA are ecological rucksack and material per unit of service.

The mass balance indicators, physical and economic trade balance indicators, identify changes in the stock of an economy. These indicators combined to socio-economic indicator of gross domestic Product (GDP), can explain the static or dynamic framework the development of an economy, helping to predict consumption and production trends for decades later.

2.4.2.1 Indicator of Ecological Rucksack

The indicator of ecological Rucksack is also known as Material intensity indicator or indicator of Material intensity per unit of service (MIPS). This indicator is about the efficiency of resource consumption as the use per unit results [103]. This indicator indicates the amount of material removed from nature that is needed to produce goods, considering the accumulation of waste and emissions during all the stages of the product or service life cycle and the range of resources used.

The ecological rucksack measures material in the categories of raw materials, abiotic, biotic raw materials, and soil movement (agriculture and forestry) [104], while the ecological footprint measures the human demand of air and water on nature [105].

The indicator of the ecological rucksack is used to reveal the production efficiency and the environmental load produced by a product or service life cycle phases (extraction, production, marketing, use, and recycling or dump), and even a consumer lifestyle (TAKEDA AWARD, 2001). Therefore, it represents an indicator of sustainability that is directly linked to regional production or management of the regions providing inputs.

2.4.2.2 Material intensity indicator per service

The indicator known as *Material Input Per Service (MIPS*) estimates the environmental cost of executing a product or providing a service throughout the life cycle of the material, considering potential environmental aggressions and including possible recycling [103]. MIPS is a measuring method of consumption of biotic, abiotic materials, water, soil, air, and electricity. Included in databases, MIPS can be an indicator of systematic application in the trusted sustainability performance comparison [64].

MIPS was created by the Wuppertal Institute and represents the total use of material that is required to produce a given service unit. MIPS has been applied to account for substances, materials and products in industry sectors or regions [106]. This indicator makes possible to estimate the environmental impact of processes, products and services and to compare them [107,108]. MIPS contributes to the development of environmental policies for the management of hazardous substances and the assessment of environmental impact of products.

In theory, MIPS considers the entire life cycle (from the cradle to the grave) [105], since it considers all material consumed in function of a service during the entire life cycle of the product [108]. However, in practice, measuring all the material input in all the processes of the life cycle of a product is extremely complicated and tends to be done in parts with boundaries that limit some processes.

2.4.2.3 Physical trade balance Indicator

This indicator estimates the amount of natural resources involved in the extraction, production, import and export of primary materials or manufactured materials from various sectors traverses the boundaries of an economy, through analysis of physical import and export data [109,110].

PTB (ton) = importation (ton) -exportation (ton)

Being PTB, the Physical Trade Balance

2.4.2.4 Balance indicator for an entire economy

The main indicators of balance for wide economy are the inputs and outputs of energy materials, substances or an economy. However, more detailed studies consider also consumption, productivity, and socioeconomic indicators. Therefore, the indicators are:

- Input: domestic extraction used (fossil fuels, minerals, biomass), unused domestic extraction (mining, quarry and harvesting) and of total material requirement (including associated import flows);
- Output: domestic output processed, domestic output total and total output of material. Representing emissions and waste, losses in the use of products, dump unused extraction and export;
- Consumption: domestic material consumption and total material consumed;

- Balance: adding liquid to the stock and the physical trade balance (including indirect flows associated with imports/exports);
- Productivity: productivity indicator of material and direct material productivity;
- Social economic indicator the gross domestic product (GDP).

These indicators show details of the MFA method applied throughout an economy.

2.4.3 Methods of MFA

The main methods of MFA serve as guides, but commonly are tailored to suit the scope of the study on the basis of the facts available.

2.4.3.1 Material Flows Analysis - inputs and outputs (MFA-IO)

MFA-IO uses the approach *top-down* for macroeconomic systems, describing monetary transactions between sectors in IO tables, to determine the life cycle impacts of any category of final demand (as consumption or export). With MFA-IO, sectoral emissions are accounted to describe all operations of an economy though the balances analysis of system´s inputs and outputs. In other words, variations of the stock on the basis of importation, exportation, production, and internal flows in the atmosphere, emissions in the lithosphere and hydrosphere [70]. MFA is applied to various industries and/or spheres of the planet, such as:

- Industry, business and services/agriculture and forestry;
- Private domestic environment;
- Waste management/waste water management.

Studies of MFA-IO uses tables and arrays of inputs and outputs of energy and materials.

2.4.3.1.1 Input and output Tables

The physical, monetary and hybrid tables of inputs and outputs are consolidated tools in MFA-IO and MEFA studies. They document the inputs and the outputs of material, substance and/or energy in performing services, forming an array [70,111]. The physical tables contain physical data and are called *physical input-output table* (PIOT) [112]; the monetary data tables are called *monetary input-output table* (MIOT) and the mixed are called *hybrid input-output table* (HIOT) [112–117].

Table 2.2 shows a model for a matrix table used for documentation of inputs and outputs in any system. Such tables are composed of three arrays of inputs and outputs of materials, substances, or energy (M/S/E) in two services to be filled with physical, monetary or mixed data.

Table 2.2 - Base of matrix for the input and output flows

			OUTPUTS					
			Service A			Service B		
			M/S/E 1	M/S/E 2	M/S/E 3	M/S/E 1	M/S/E 2	M/S/E 3
INPUTS	Service A	M/S/E 1	Z^{AA}_{11}	Z^{AA}_{12}	Z^{AA}_{13}	Z^{AB}_{11}	Z^{AB}_{12}	Z^{AB}_{13}
		M/S/E 2	Z^{AA}_{21}	Z^{AA}_{22}	Z^{AA}_{23}	Z^{AB}_{21}	Z^{AB}_{22}	Z^{AB}_{23}
		M/S/E 3	Z^{AA}_{31}	Z^{AA}_{32}	Z^{AA}_{33}	Z^{AB}_{31}	Z^{AB}_{32}	Z^{AB}_{33}
	Service B	M/S/E 1	Z^{BA}_{11}	Z^{BA}_{12}	Z^{BA}_{13}	Z^{BB}_{11}	Z^{BB}_{12}	Z^{BB}_{13}
		M/S/E 2	Z^{BA}_{21}	Z^{BA}_{22}	Z^{BA}_{23}	Z^{BB}_{21}	Z^{BB}_{22}	Z^{BB}_{23}
		M/S/E 3	Z^{BA}_{31}	Z^{BA}_{32}	Z^{BA}_{33}	Z^{BB}_{31}	Z^{BB}_{32}	Z^{BB}_{33}

The *National Accounting Matrix including Environmental Accountancy* (NAME) contains matrixes with data inputs, and outputs of material stock, water and/or energy at national level, with denotation of physical units and airborne emissions outputs, expressed in tones. Considering ordinary country data (import, export, trade, suppliers, intermediate usage, end of use) and emissions from services industries and households [118].

Moreover, Matlab [119] or other simulation programs are used for numerical analysis, while CML-IA [120], the SimaPro [83], version 6 and newer, are applied for analysis of inputs and outputs (IO) and for hybrid LCA combined with databases.

2.4.3.2 Material flow accounting for economy-wide (MFA-EW)

The *Economy-Wide Material Flow Accounting* (MFA-EW) method has been developed since mid-1990 with the cooperation of institutes and research organizations, aiming to evaluate the performance of an economy [42], accounting for minerals and construction industry in regional or national scale.

This method compiles statistics linking the flows of materials and natural resources to meet national economies. This method covers the changes in material stocks within the economic system, and the material outputs to other economies or to the environment. Under *top-down* approach, MFA-EW evaluate descriptive statistics, in physical units as tones per year.

MFA- EW and its indicators help to understand and monitor of issues related to the consumption of materials. It gives an overview of the intervention of an economic system in the material flow and an economy of material flows [121]. Therefore, a MFA-EW study can find out if a country is dependent on others in terms of natural resources or if an economy has sustainable production, using the least possible amount of natural resources.

In 2000, the WRI published "*The weight of Nations*" [122], which showed studies of MFA-EW for Austria, Germany, Japan, Norway and the United States. In this document indicators of material flows were presented, including the GDP indicator in systems modeling. Moreover, the term *Material Flow Accounting* was presented.

Energy accounting can be done based on the same principle of MFA and it was entitled for *Material and Energy Flow Analysis (*MEFA). Fig. 2.6 presents a conceptual representation of MFA-EW and MEFA, where incoming flows (imports and domestic extractions) and outputs (of domestic and export dumps/productions) affect the environment.

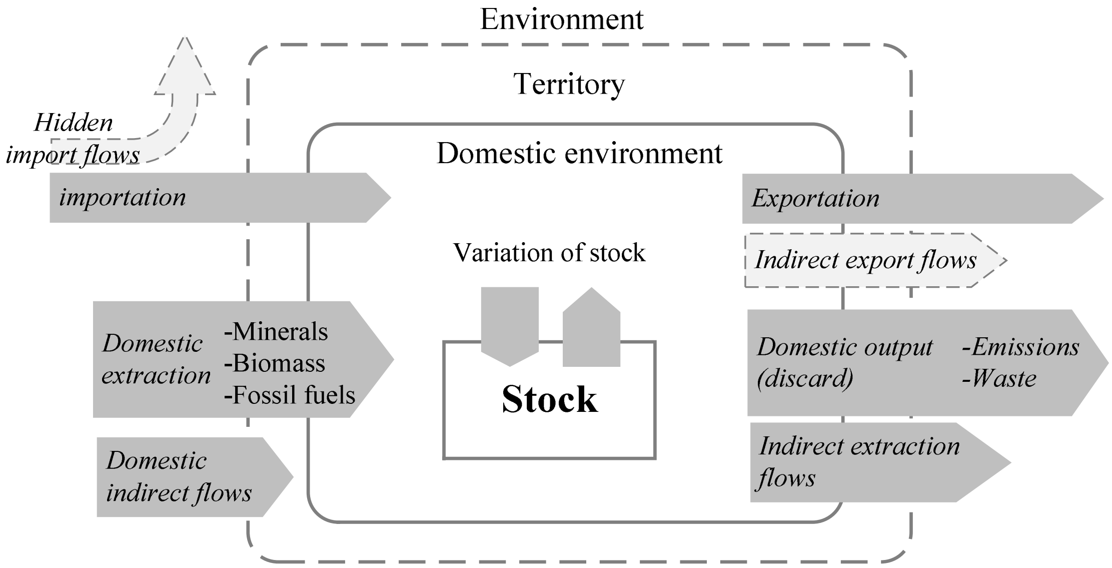

Fig. 2.6 - Conceptual Representation of modeling systems

A MFA-EW study should cover stocks and flows that are not covered by financial accounting: the waste stream, exhausts, or stock of obsolete products [91]. Hashimoto talks about practical problems in identifying flows of materials and calculate the indicators, such as: the difficulty in capturing by-products and products that are not captured in current statistics used, to distinguish between by-products and products used, and identify the stocks of products [123]. Therefore, MFA-EW approaches based on economic indicators tend to use quantitative data of physical materials.

In a detailed analysis, we listed advantages and disadvantages of the MFA-EW.

Advantages:

- It is used for error checking. MFA uses physical limits providing building processes for inconsistencies in accounting and identification of indeterminate streams [124,125];
- It provides an integrated view of the interactions between materials, energy and environment, increasing the transparency of the accounts of MFAs. Apparent and hidden

movements of bulk materials in an economy are identified, catalogued and calculated [125,126];

- It evaluates the mass balance, identifies trends in inventory additions and evaluates the sustainability. This method uses available metrics such as the efficiency of the extraction of raw materials to evaluate sustainability within a specific unit of the economy [125–127];
- It extends the temporal and spatial effects of social and industrial activities;
- It has been used to reveal mistakes in identifying the biggest polluters, presented consumers and major polluters than producers [125,128].

Disadvantages:

- It serves for analytical purposes, but not for comparatives ones. The lack of standards for its use, and verification of data methodology [125,128] prevents the comparison between different materials;
- It is static, because it calculates the balance in one year, and not directly for long term evaluation. However, it requires that we collect a large data set to cover several years [125];
- It focuses in a single substance, not identifying environmental impacts in the replacement of substances. LCA can be combined with MFA to overcome this deficiency [124,129].

MFA-EW uses the input, output, consumption, production and balances to analyze the flow of the system. Table 2.3 shows the acronym, the name and description of each indicator.

The temporal limit of one year is the period considered appropriate to analyze the material balance of a region, mainly for reasons of availability of statistical data. Hence, MFA-EW is a static method. The analysis with wider temporal border would be a systematic use of MFA-EW in several years, which is extremely laborious. For this reason, Dynamic MFA-EW was created.

Table 2.3 - Economy indicators. Based on [110]

	Acronym	Name	Equation
Input	DEU	Domestic used extraction	
	DMI	Direct input of material	DMI=DEU+ importation
	TMR	Total material requirement	TMR=DMI+ DEU+ indirect imports resources extraction
Output	DPO	Domestic processed output	DPO=emission+ waste
	TOD	Total domestic output	TOD=DPO+ deposition of non-used extraction
	TMO	Total output of material	TMO=TOD+ exportation

Consumption	DMC	Domestic material consumption	DMC=DMI-exportation
	TMC	Total Material Consumption	TMC=TMR-exportation- indirect flows associated to exports
Balance	NAS	Net addition to the stock	NAS=DMI-DPO-exportation
	PTB	Physical trade balance (including indirect flows associated with imports/exports)	PTB=importation-exportation
Productivity	GDP/ TMR	Total material requirement	
	GDP/ DMI	Domestic processed output	

2.4.3.3 Dynamic MFA –EW

Dynamic MFA –EW method estimates the future flows (in years or decades) through analysis of historical development patterns of physical stocks and flows. Covering flows of material, energy emission and waste inside the geographical border of a country.

With *Dynamic-MFA*, we can achieve a historical reconstruction of the largest streams in the system, possibly in the absence of data, adopting other data regions, and validating the model by comparing the measurements with those of other models[64].

The input streams are the materials taken from the territory of the system and fresh materials or products imported to meet the demand for domestic consumption and for export (after transformed). The stock is dynamic because it is produced over a longer time and is in constant change. The outputs are produced by production losses, wear and tear, and obsolescence of materials. Since the stock variation is influenced by socioeconomic factors (characteristics of development of society and population variation and urban lifestyle of society), the inputs and outputs vary at the same rate [130].

Among countless relevant studies which used this method, we cite Müller and Hu. Müller *et al.* [94] who published an extensive review of MFA-dynamic in 2009 analyzing streams of metals during the fifteen previous years. Hu [130] performed a work of MFA-dynamic applied to case studies of Chinese housing, correlating entries of building materials and waste outputs, with socioeconomic data to analyze long-term impacts on urban growth in Beijing (China), especially regarding changes in steel and iron.

2.4.3.4 Life cycle assessment combined with MFA

Life cycle assessment is a methodology to analyze impacts of products and services throughout modelling, inventory and life cycle impacts calculation. LCA´s standards ISO 14040 series [30,131] suggest that it should be carried out in four steps: setting goals and scope (spatial and temporal borders, methods and indicators, functional unit), life-cycle inventory (process modeling and estimation of material inputs and outputs), impact assessment of the life cycle and interpretation of results. Currently, this methodology is supported by international databases of life cycle inventories of numerous processes and materials in several countries and global estimates with advanced mathematical treatments to minimize uncertainties [82,132].

According to Brunner[64], MFA can be considered part of an LCA study, where the system in modeled identifying the processes, inputs and outputs. However, the nature of MFA is working in large geographical scales, with a limited number of substances, seeking to meet the needs of management, and working with few substances. While LCA tends to be extremely meticulous regarding to substances and internal flows of intermediate processes by-products [133].

Therefore, LCA is geared towards the analysis of processes (generally in the production of products) as MFA is geared towards the analysis of materials, substances (SFA) or energy (MEFA). In addition, MFA can be achieved under the concept of "black box" (with sealed or unknown processes, without detailing the internal flows), analyzing only substances which exceed the boundaries of the system or under the concept of "gray box", with system processes partially analyzed [91,134]. The use of the concepts of black box and grey box simplifies the process of balance sheet analysis in the system. So, MFA has been combined with LCA to generate a systematic framework of physical flows of natural resources while LCA is a tool for environmental assessment throughout the life cycle of the system [135].

Fig. 2.7 summarizes the key features the MFA, LCA and MFA. The Union of the MFA and LCA allows assessing large scale geographical, more detailed and accurate form. While MFA calculates the amount of extraction of natural resources and material flows, LCA evaluates the influence of each phase of the system in the environmental impact.

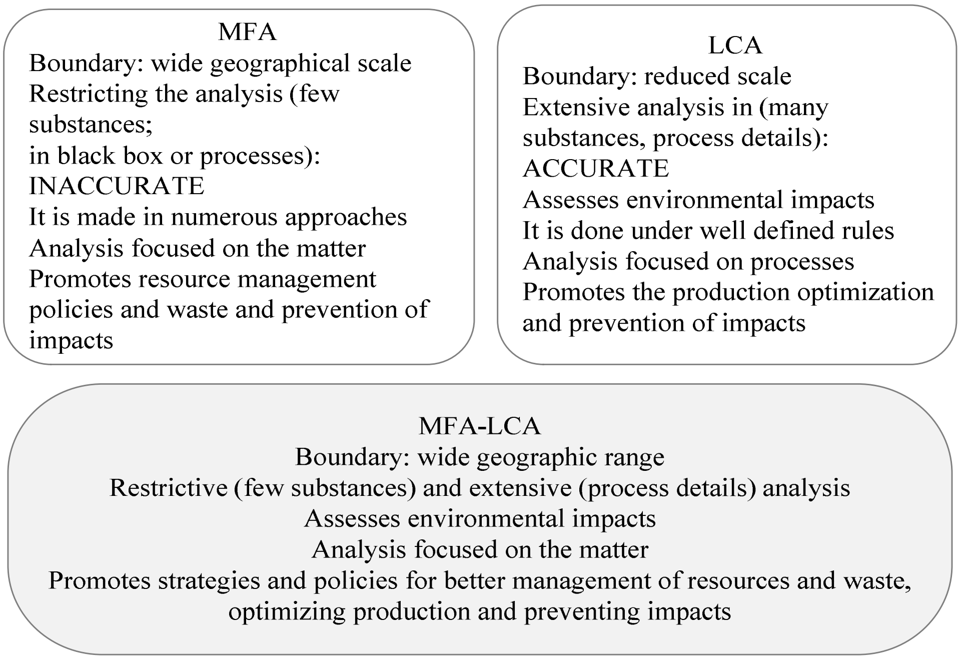

Fig. 2.7 - The main features of MFA, LCA and MFA-LCA

Therefore, MFA-LCA method is used as a systematic approach to identify sustainable practices, taking advantage of the characteristic of LCA studies on the level of detail and coverage of numerous substances, and the completeness characteristic of MFA studies.

In other words, MFA-LCA is a method that can establish an inventory (LCIA), while the LCIA can assess impacts found in the results of material flows determined on MFA to different systems. Venkatesh *et al.* [136] used MFA-LCA to analyze the life cycle impacts of the Oslo pipelines stock. Rincón *et al.* [137] evaluates life-cycle impacts of facades of buildings in Spain. As well as, Guo *et al.* [134] assess impacts of life cycle of materials contained in stock of urban road system in Beijing.

Hence, not only several methods exists, but also there is a significant mix between methods to meet the desired scope.

2.5 Bibliometric analysis applied to MFA

For the survey of papers in Scopus, first, we analyze publications in the repository based publications Scopus [35], then we generate bubble charts in different categories through VOSviewer [36], and finally we analyze the results.

The parameters used in Scopus for the analysis of bibliometric were *“keywords”*, *“every year”*, *“all types of publications”*, limited to the *“English language”*. The parameters used in VOSviewer to generate the publications network were *"repeated expressions"* (10 repetitions) for the graphs of *"clusters", "years of publication" and "impact factor"* (IF). For the graph of origin and countries authors, we use the parameter "*documents*" for the graphs "*countries of origin"* and "*authors*".

Table 2.4 shows the expressions used in the pursuit of Scopus and the number of publications found and the preparation of graphics.

Table 2.4 - Characterization for publications search

Search	Count of Title	Group, year, FI	Country and author
Material Flow Analysis	1,113		X
Material Flow Analysis AND economy	215	X	
Material Flow Analysis AND economy-wide	41	X	
Material Flow Analysis AND industry	287	X	
Material Flow Analysis AND input-output	96	X	
Material Flow Analysis AND MEFA	4	X	
Material Flow Analysis AND metabolism	159	X	
Material Flow Analysis AND regional	85	X	
Material Flow Analysis AND review	68		

2.6 Consolidated results and discussion

2.6.1 Compilation of events for sustainable development

Fig. 2.8 presents a chronological chart of major events related to sustainable development as a timeline for sustainability awareness.

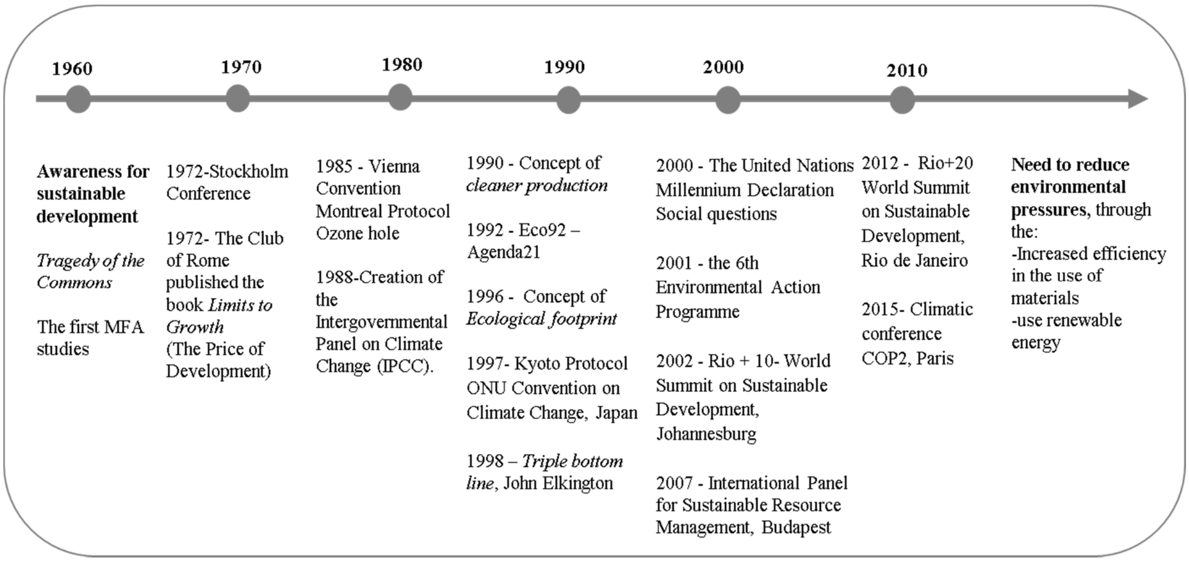

Fig. 2.8 - Timeline for sustainable development

2.6.2 Featured articles used in literature review

The range of MFA publications is vast. Table 2.5 highlights some publications that apply various methods and reviews:

Table 2.5 - Publications about MFA in different approaches and literature reviews [49,70,111,134,138–143]

Author	Ciacci *et al.*	Li *et al.*	Hass and Popescu	Liang *et al.*	Bao *et al.*	Hu *et al.*	Steinberger *et al.*	Guo *et al.*	Reisinger *et al.*	Krausmann et al.
Year	2014	2013	2011	2010	2010	2010	2010	2010	2009	2004
Method	MFA	MFA-EW	MFA-EW	Based on MFA-IO	Review	MFA-Dynamic	MFA-WE	MFA and MEFA)	Review	MEFA
Material/substance	Aluminum	Material	Material consumption per capita and Market	Material, energy and air pollutants	-	Steel	Materials (construction minerals, fossil fuels and mining / industrial minerals)	Construction material and construction waste	-	Materials: fossil, industrial minerals, construction materials and biomass
Object	Vehicles	Anthropogenic metabolism	Anthropogenic metabolism	Anthropogenic metabolism	MFA in national, regional and industrial levels	Residential buildings	Anthropogenic metabolism	Urban residential buildings	MFA and its indicators	Land usem socioeconomic metabolism and land-use
Time	End of life	2000-2010	2000-2007	2005-2020	1991-2009	1900 - 2100	2000	1949-2004	Until 2009	1950-2000
Local	Italy	China	European union	Suzhou, China	-	China	175 countries	Beijing, China	N/A	Austria
Focus	Waste from stock in use	Waste (aiming to suggest waste management policies to address China's circular policy).	Market dynamics	Direct and indirect effects of energy consumption and emission of polluting gases into the atmosphere	Overview on development of MFA methodology	Construction and demolition waste	Consumption and productivity analysis to dematerialization of development	Urban building development analysis to sustainable development	Overview	Economic growth and progress around sustainability.
Keywords	Aluminum recycling In-use stock Material flow analysis SFA Scrap generation Top-down approach	Recycle Reuse Reutilisation Reutilisation-extended EW-MFA	N/A	Energy Analysis Inut-output model Suzhou	Material flow analysis Environment-economic systems Circular economy Sustainable development	Industrial ecology Dynamic Material Flow Analysis Iron and steel Housing China	MFA Resource productivity Global material use Gini coefficient Dematerialization Income elasticity	Concrete Dynamic modeling GDP Industrial ecology Per capita floor area Waste projection	N/A	Socio-economic metabolism Material flow accounting Energy flow accounting Human appropriation of net Land use Ssustainability

2.6.3 Bibliometric analysis

Fig. 2.9 shows the graph for "clusters" where expressions are grouped according to the occurrence of repetition and interrelation between them. We draw ellipses, differentiated by colors, involving the related groups, and label them according to the main features of the publications. The red cluster suggests the application of the MFA for waste management (WMAG). The blue cluster shows the use of MFA and LCA in industry and construction (MFA & LCA). The green cluster suggests MFA-EW publications, studying flows based on consumption and the trade trends. The yellow cluster represents publications on substance flows and water from urban metabolism of cities (URBMT). The purple cluster suggests to study market trends and growth of economic systems (MKT).

The expressions "*trend*", "*construction*", "*ecosystem*", "*economic growth*", "*recycling*", "*United States*", and "*Japan*" are particularly important because they are linked to more than one group. Regarding the construction sector, this graphic suggests that its studies using MFA are directly linked to waste management, MFA combined with LCA and MFA-EW.

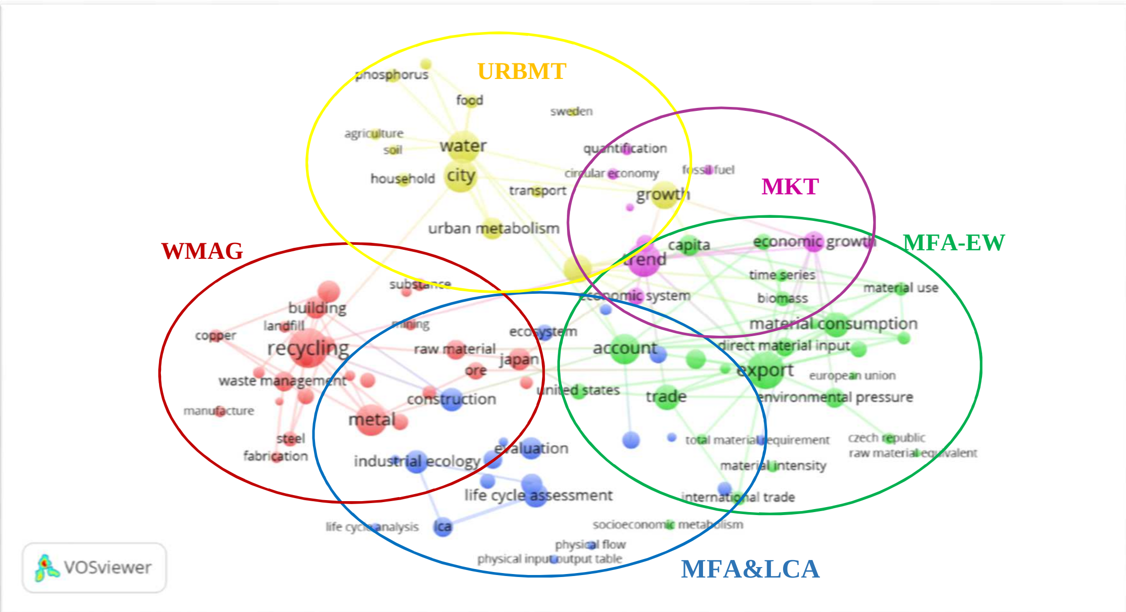

Fig. 2.9 – Publication by "*clusters*".

Fig. 2.10 shows the graph for "year" where the repeated expressions fall within a certain time interval. The graph shows the development of MFA publications, highlighting high occurrence applying the economy in 2008, subsequently, product analysis in 2009, energy in 2010, industrial ecology in 2011 and urban metabolism in 2012.

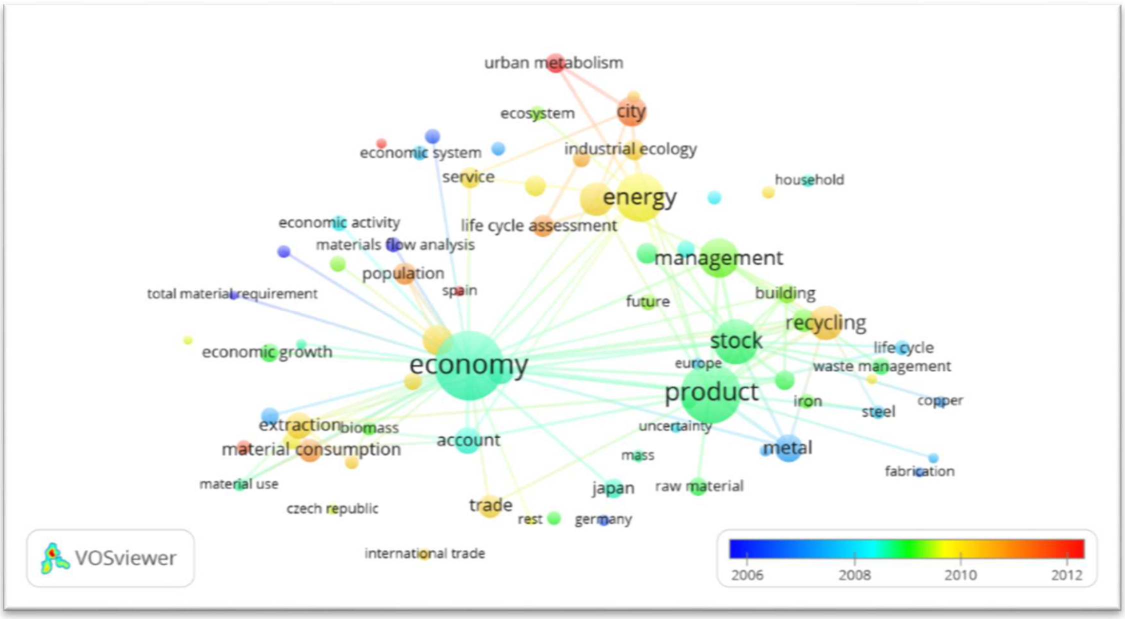

Fig. 2.10 – Publications by “years”.

Fig. 2.11 shows the graph for "Impact Factor", where repeated expressions fall within the range between 0.6 and 1.6 of the impact factor. The graph shows that the greatest impact factors of publications are focused on the analysis of urban metabolism, followed by energy and product. Finally, analysis of savings comes in larger quantities, but with a lower impact factor.

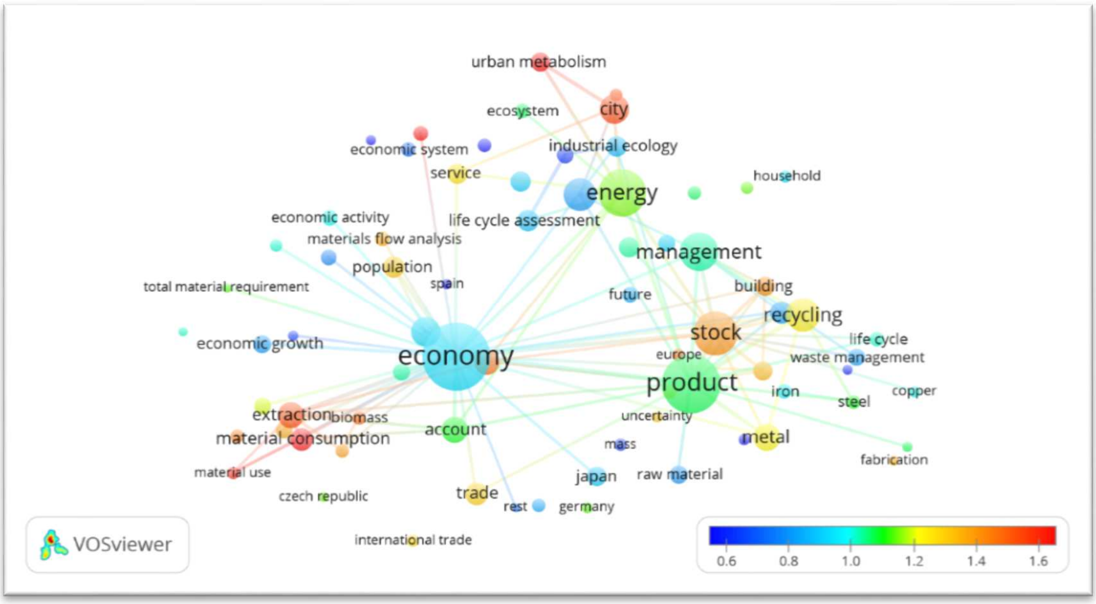

Fig. 2.11 – Publications by "Impact Factors".

Fig. 2.12 shows the graph for "Country", where documents from the search "Material Flow Analysis" in the countries of origin of most publications and the interrelationship between them are presented. Among the countries, which increased representation on MFA publications numbers were the United States (US), followed by Germany, Austria, China and Japan.

The chart makes clear five partnerships between countries in the study of MFA, which are listed in decreasing order of number of publications. The absence of links between some countries to others in the group suggests that these countries have publications on the same theme, but without a direct partnership with other groups.

1. US, Malaysia, Belgium, Taiwan, Saudi Arabia and Mexico. More South Africa isolated;
2. Austria, China, Japan, France, Denmark, Thailand, Vietnam and Italy. More Poland and Brazil isolated;
3. Germany, Czech Republic, Spain and Finland. More Portugal isolated;
4. Australia and Canada. Mors New Zealand isolated;
5. Norway.

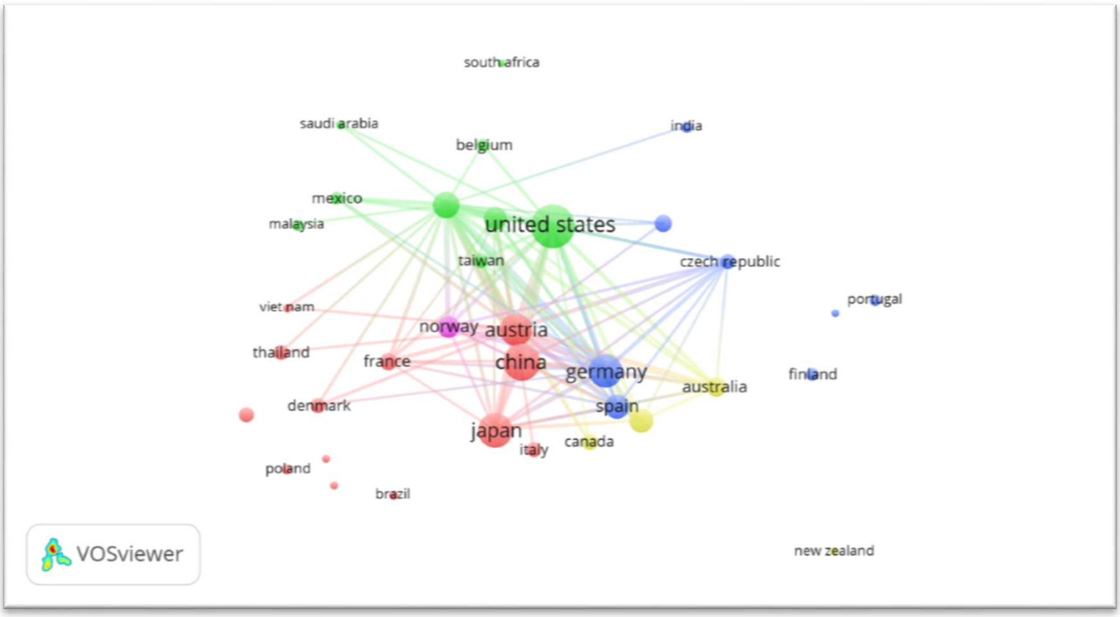

Fig. 2.12 – Publications in "Country".

Fig. 2.13 shows the graph for "Authors and co-authors" where documents from the search "Material Flow Analysis" present the greatest contribution of authors and their interrelations. This chart brings together authors and co-authors with publications in partnerships and illustrates in colored bubbles. For better understanding of partnerships, the authors and their affiliations are described below:

1. Purple:

• Daigo I: School of Engineering, University of Tokyo, Tokyo, Japan.

2. Yellow:

• Graedel T. E., School of Forestry and Environmental Studies, Yale University, United States.

• V. Wohlgemuth, College of Technology and Economics (HTW) Berlin, Germany.

3. Blue:

• K. Nakajima, National Institute for Environmental Studies, Japan.

• Kondo Y., Waseda University, Japan.

4. Green:

• Kovanda J., Charles University Environment Center, Czech Republic.

• Bringezu S., Wuppertal Institute for Climate, Environment and Energy, Germany.

• Eisenmenger N., Department of Social Ecology, IFF;

• Moriguchi Y., University of Tokyo, Japan;

• Hashimoto S., Graduate School of Engineering, The University of Tokyo, Japan.

5. Red:

• D. Müller, Ins. of Water qlty. and Waste Mgt., Vienna University of Technology, Austria.

• Bader H.-P., EAWAG, Department SIAM, Switzerland.

• Brunner P.H., Ins. of Water qlty. and Waste Mgt., Vienna University of Technology, Austria.

• H. Rechberger, ETH, Swiss Federal Inst. Technol. Zurich, Dept. of Resource and Waste Mgmt., Switzerland.

• J. Fellner, Vienna University of Technology, Austria.

• Eckelman M.J., Dept. of Civil and Environmental Engineering, Boston, Massachusetts, United States.

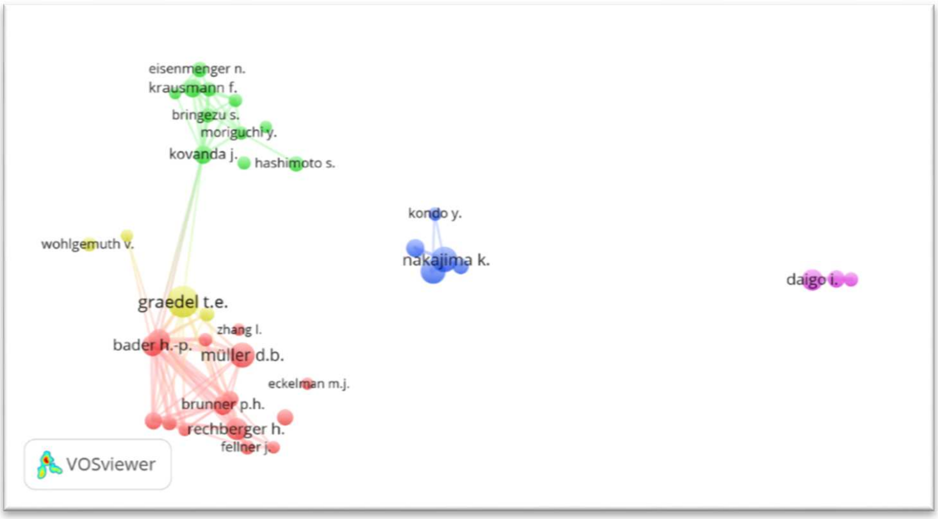

Fig. 2.13 – Publications in “Authors and co-authors”. Made by VOSviewer

The results show that countries of the European Union are connected with other groups of the European Union. Although important publications on waste, the European Union tends to make analysis at the macro level: market and global socio-economic development, the European Union and European countries. In contrast to Europe, China and Japan focus their analysis on their geographic limits. China tends to analyze waste and urban buildings aiming at internal sustainability policies, while Japan seeks to preserve resources with the efficient use and recycling of materials.

US are connected to large and small groups. Countries like Brazil, Portugal, Finland, South Africa and New Zealand have isolated studies, disconnected from all or other groups. According to the results, Latin America does not have large nucleus of MFA research; this explains why there are few inventories from this continent in international databases.

The strategies presented in Table 2.1 show that the United States has studies in several areas, especially inventorying the metal stock and their flows. China's strategy is focused on the domestic economy, the reuse and recycling of waste. Japan's strategies confirm the trends of resource conservation. Comparing the data in this table with bibliometric analysis (Fig. 2.12), we conclude that United Kingdom works in many areas, but always alone, independent of the European Union and does not exposes internationally their results.

In a search on Scopus for articles with “Material Flow Analysis” and “Latin America” and “Material Flow Analysis” and “Brazil” between 2009 and 2016, the repository presented few publications Table 2.6. Among them, half showed Latin America and Brazil as participants in the international trade. Consequently, only half of the few publications analyze the stock and flows of materials or substances of these places.

Therefore, the results demonstrate that US connected to several research centers and their partnerships between researchers groups, especially European countries. And these European groups also address Brazil and Latin America as part of material flows in the global trade balance studies. Studies of the stock of material and its flows in Latin America are less significant.

Table 2.6 - Main studies found in bibliometric analysis with Latin American and Brazilian participation [144–153]

Author	Schaffartzik, A et al.	Duan, H et al.	West, J. and Schandl, H.	Manrique, P.L.P.	Dittrich *et al.*	Muñoz, P. *et al.*	Cavalett, O. and Ortega, E.	Tanimoto, A. H. *et al.*	Ossés de Eicker, M. *et al.*
Year of publication	2014	2014	2013	2013	2012	2011	2010	2010	2010
Local	Soviet Union and its allies, Asia, the Middle East and Northern Africa, Latin America and the Caribbean, and Sub-Saharan Africa	Global	Latin America	Argentina	World-wide	Latin American countries (Brazil, Chile, Colombia, Ecuador and Mexico)	Brazil	Brazil	Brazil
Material/substance	Biomass- to a minerals	Export of used electronics from the United States (U.S.)	Biomass	Fossil fuel, construction minerals, industrial minerals, ores, biomass	Physical trade	North (N)-South (S) trade in the Americas	Biodiesel production from soybean	Copper life cycle	Triple superphosphat
Boundary time	1950–2010	2010	From 1970	1970–2009	1962 and 2005	2003	Not identified	2005	Not identified
Methods	Global material flow dataset	Trade data approach	MFA-EW, material use and material efficiency for the region	MFA-EW, social metabolism	Physical trade flows, direct and indirect physical trade balances	Multi-regional input–output analysis	Emergy Accounting (EA), Embodied Energy Analysis (EEA) and Material Flow Accounting (MFA)	Substance flow analysis, modelling	MFA based on LCIA, modelling the production
Keywords	Global material use Industrial metabolism Material flow accounting Metabolic profiles	Global material use Industrial metabolism Material flow accountingMetabolic profiles	Latin America Material efficiency Material flow accounting Resource productivity Sustainable resource management	Argentina Ecologically unequal exchange Extractive economies Industrial ecology Material flow analysis (MFA) Social metabolism	Burden shifting Global trade Indirect flows Material flow analysis (MFA) Materials embodied in trade	International trade Latin-America Material flow analysis (MFA) North-South trade Unequal exchange World-system theory	Biodiesel Embodied energy Emergy accounting Material flow accounting	Copper Copper consumption Copper cycle MFA SFA of copper	Brazil Database Ecoinvent Fertilizer Industry LCI LCIA Latin America

2.7 Conclusion

MFA has been used to assess material and energy flows across different systems and metabolisms around the word. MFA is usually combined with other methodologies, which are bottom-up or top-down approaches, in multidisciplinary studies. Consequently, its concepts can be misunderstood, resulting in conceptual mistakes in MFA studies. This study contextualizes, describes and analyses different methods, applications and indicators of MFA through a literature review and bibliometric analysis publications from clusters, years, authors, co-authors, countries and impact factor.

Results synthesize and assess variations of MFA methodology described in the extensive literature and discuss trends and strategies on MFA studies according evaluation of publications on these subjects. The literature review explains features of MFA in the main methods: input-output, economy-wide and combined with Life Cycle Assessment, applications, and indicators. Results of bibliometric study shows that the most recent publications have the highest impact factor and focus on the metabolisms of cities assessment through the study of material consumption. Moreover, results highlight strategic partnerships between countries by topics covered, as an active participation of United Sates, European Union, Japan and China and passive participation in Latin America among the articles published between 2009 and 2015, deposited in the Scopus repository.

Our analysis provides an overview for a better understanding of the method, application and focus on the use of MFA. Consequently, this study contributes to systematic applications, including MFA combined with other methods of analysis of environmental impacts. Therefore, future research should assess the criteria of the most cited articles of MFAs, describing the geographical boundary of the studies, affiliations of the researchers, fields of study and impact factors.

2.8 Nomenclature

DE	*Germany*
UK	*United Kingdom*
USA	*United States of America*

EU	*European Union*
MFA	*Material Flow Analysis*
WCED	*World Commission on Environment and Development*
UNIDO	*United Nations Industrial Development Organization*
MFA-EW	*Material Flow Analysis (or Accounting) Economy Wide*
MEFA	*Material and Energy Flow Analysis*
MFA-IO	*Material Flow Analysis-input-output*
LCA	*Life Cycle Assessment*
PIOT	*Physical input-output table*
MIOT	*Monetary input-output table*
HIOT	*Hybrid input–output table*
MIPS	*Material Input per Service*
MI	*Material Intensity*
PTB	*Physical Trade Balance*
OECD	*Organization for Economic Co-operation and Development*
IPCC	*Intergovernmental Panel on Climate Change*
KR	*Korea*
JP	*Japan*
SEC	*Institute of Social Ecology*
UNEP	*United Nations Environment Programme*
GNP	*Gross national product*
ELCD	*European reference Life Cycle Database*

3 MODELING MATERIAL STOCK AND FLOWS FOR RESIDENTIAL BUILDINGS IN RIO DE JANEIRO

3.1 Introduction

With the world population growth, the need for housing and urban infrastructure increased. It seems evident that actions for efficient use of raw material and for waste management must be taken aiming to achieve a sustainable development of the construction sector. The construction sector exchanges large volumes of materials and waste between the anthropogenic and the natural environment. Between 30% and 50% of natural resources consumed in Europe correspond to the construction sector, mainly materials from mineral origin [154].

Considering the whole life cycle, materials used in buildings contribute to raw material scarcity and pollution. Consequently, they incorporate impacts to environmental loads of the buildings. The exploitation of natural resources for construction materials manufacturing, waste treatment and disposal, and materials transportation, leads to resources depletion and environment pollution [155]. Once the buildings are part of cities, their environmental loads and their general dynamics interfere directly in city's metabolism.

The construction sector has been searching for efficiency in the use of building materials, reduction of use of natural resources and prevention of impacts from waste treatments in order to meet the sustainable development standards [11–14,156,157]. Since the 2000s, the European Union has been promoting strategies and policies to improve the efficient use of resources and stimulating recycling, reuse and waste exchange between companies European Union (EU) [11–13,158]. Accordingly, Japan created the *3R strategy* (reduce, reuse, recycle) and China created the *Circular Economy* Law, as strategies to achieve efficiency in the use of materials [14]. In addition, Austria, Germany, Switzerland and Australia have been mapping and documenting results of material flows in databases and developing indicators of sustainability and models inventory buildings materials [15,159,160].

Also since the early 2000s, Brazil has been trying to adapt to the global trend of *dematerialization of the development*. That is, Brazil seeks to enhance the efficiency of materials use and, consequently, to promote the development of sustainable progress. The Resolution 307/2002 of the National Environmental Council (CONAMA) [17,161] and its updates guide the efficient management of construction waste in Brazil. The National Policy of Solid Waste (PNRS) [16], instituted in 2010, encourages the industry and the construction sector to use sustainable materials and recycling waste. Moreover, Standards, as NBR 15575 [18], presents ways to improve residential buildings performance and to extend their lifetimes. In addition, environmental certifications such as LEED for homes [162], *Aqua* [163] and *Selo Casa Azul* [164] have been implemented even in the residential sector process. Consequently, Brazil expects to reduce material consumption and the impacts from construction and demolition waste (CDW), promoting the search for efficiency in the use of materials and reducing of environmental impacts of the life cycle of buildings.

Material Flow Analysis (MFA) has been used from different methods and approaches to survey material flows from buildings and, as well, to predict waste generation. MFA studies the metabolism of societies, in the sense that analyzes the interaction between society and nature through various disciplines [32]. Once the local characteristics interfere in the metabolism of a city, knowledge about the urban areas is crucial to promote sustainability [165]. Material Flow Analysis (MFA) has been used to recognize building stocks and their materials and waste flows in cities, countries and group or countries. MFA is performed through analysis of material consumption, physical trade balance, demographics and / or economic indicators, aerial photographs, and historical and urban diagnoses by academics and governments. Material exchanges between the stocks and environment during their life cycles generally are estimated by statistical models, which use historical distributions to predict the dynamics of the stock and possible scenarios in the future.

In this context, this study aims to estimate the building stock of the city of Rio de Janeiro and analyze the recent materials and waste flows in order to get the first estimates of this stock. This study applies a holistic approach based on the Material Flow Analysis methodology to survey the materials in the building stock of the city of Rio de Janeiro and their materials and waste flows.

3.2 Literature review

3.2.1 Material Flow analysis used to estimate materials in stocks

MFA for estimation of materials in use in building stocks can be made from *bottom-up* or *top-down* approaches. MFA in *bottom-up* approach promotes inventories in small scales (as cities and regions) through the evaluation of architecture, construction and urban variables. On the other hand, MFA in *top-down* approach promotes analysis from stocks of materials or substances through *economy-wide indicators* (input, output, balance, consumption and productivity) [45,110,148]. The statistics data of material consumption and indicators of economy, market and production usually are available from countries; cities and regions seldom have this kind of information documented and available for searches. In addition, MFA is *static* when it is applied to models with temporal border of one year; it usually is done by inventories. *Dynamic* MFA uses models with largest temporal border; it frequently uses simulations to evaluate inputs and outputs for tens of years [94,166]. MFA in *top-down* and *dynamic* approaches has been used to survey materials and substances stocks, especially from metals, in countries and globally. MFA in *bottom-up* and *static* approaches have been used to estimate stocks in regional scale.

A literature review (Table 3.1) shows that MFA in *top-down* and *dynamic* approaches generally, but not always, assesses systems considering larges geographical boundaries and time scales; when applied for a country, it analyzed its role in international trade. The *long term* approach, that is used by Schaffartzik [144], is similar to the *dynamic* approach. As we can see in this review, MFA combined with different methods are quite common when the study scope encompasses other analysis. Wiedenhofer and collegues [167,168] promote a *static* analysis to recognize Europeans building stocks, that gave an overview about it, and after a they promoted a *dynamic* one to assess its flows and impacts.

Table 3.1 - Review of studies from MFA for investigate stocks [94,144,168–171]

Authors	Wiedenhofer *et al.*	Wiedenhofer *et al.*	Schaffartzik *et al.*	Hammer *et al.*	Hattori *et al.*	Müller *et al.*	Bergsdal *et al.*
Year of publications	2014	2015	2014	2003	2013	2014	2007
Types of stock	Residential building stock and road/railway network, maintenance and expansion phases	Construction and demolition waste stocks and flows and road/railway network, maintenance and expansion phases	The global metabolic transition	Minerals, Fossil energy carriers and biomass	In-use steel stock	Metal stocks and flows	Dwelling stock
What they analyze/do	Standing stocks of construction minerals, related material flows and recycling potentials	Construction and demolition waste: they model stocks and flows for nonmetallic minerals in residential buildings and assess its impacts	Regional patterns and trends of global material flows from material extraction, trade, and consumption	Consumption, productivity, eco-efficiency, physical trade balance	Civil engineering and building	A review of dynamic Material Flow Analysis Methods	Floor area and material use
Locals of the stock	EU25 states	EU25 states	177 countries in Soviet Union and its allies, Asia, the Middle East and Northern Africa, Latin America and the Caribbean, and Sub-Saharan Africa	City of Hamburg, Germany	41 countries	N/A	Norway
Temporal scales	2004-2009 for residential building stock and 1995-2009 by road/railway	2004-2009 and a business-as-usual scenario for 2020	1950–2010	1992-2001	2006 and 2010	1999-2013	1900-2100
Approaches	Bottom-up and Static	Dynamic	Long-term	Top-down and static	Bottom-up and static	Dynamic, bottom-up and top-down	Dynamic
How they did	Inventorying homes and roads for some years repeatedly	Analyzing case studies of buildings (72) and of roads (4)	Using Economy-wide method	Using Economy-wide method: Material input and consumption indicators per capita and GDP	An inventory using nighttime light images	Analyzing studies by a standardized model description format, the ODD (overview, design concepts, details) protocol.	Analyzing the population's demand for housing and their variables, as constructed area, lifetime, lifestyle, and material density
Objectives	To gain first estimates.	To assess the potential impacts of recycling	To get a better understanding of the currently ongoing metabolic transition and its potential inertia to achieve a sustainability transition	To show the role of Hamburg as an international harbor	To validate a methodology	To give a comprehensive overview of modeling approaches and structure them according to essential aspects	To investigate the impacts of changes in stock, including variations in material usage (concrete and wood) and material density.
Key words	Not provided by the author	Construction and demolition waste Dynamic stocks and flows modeling Industrial ecology Material flow analysis (MFA) Recycling Societal metabolism	Material flow accounting Global material use Metabolic profiles Industrial metabolism	Material flow analysis (MFA) Regional development Environmental indicators Sustainability.	Steel In-use stock Nighttime light image Time-series change	Not provided by the author	Building stock Demolition dwelling stock Dynamic material flow analysis Materials demand Trends Waste generation

3.2.2 Material Intensity and Material Intensity per Service

Material Input per Service (MIPS) is a unit used for the estimation of the environmental impacts of products and services [10,95]. MIPS represents the resources required for the execution of a service; that are removed from natural environment. MIPS is calculated by the division of the total resource input for the service by the mass of the final service. Countries or industrial sectors less developed tend to have more material losses during manufacturing or construction processes. The rate of material loss should not be neglected in order to avoid distortion in the results. The application of MIPS for the complete buildings life cycle depends on a deep survey of material and energy consumption during all phases of them.

In other words, MIPS is a unit that represents the systematic application of *Material Intensity* (MI), considering materials and energy, to services executions [41,172]. MI is the amount of material contained in a product or fractions of it [91,169,173]. MI can be used as unit for a systematic comparison between residential buildings in order to assess the efficiency in use of materials in buildings construction. The material intensity per service depends on the rate of productivity while material intensity depends on the building systems.

3.3 Methods

This study uses a method based in Material Flow Analysis to estimate materials in building stock of a city, which identifies direct interaction between construction and urban variables that affect building stock and quantifies the material consumed and their waste. The method follows *semi-dynamic* and *bottom-up* approaches. *Bottom-up* because it extrapolates a short unit to larger one. *Semi-dynamic* because it evaluates the stock behavior from the baseline year to its end of life, disregarding new buildings and extraordinary variation, such as economic fluctuations, property speculation and migration.

A building stock is built following construction and urban rules and regional characteristics; consequently, these indices and their dependency are assessed. We extrapolate construction variables (material intensity) to urban variables (total constructed area) in order to estimate the materials and waste flows of the building stock. First, we review statistical data and technical and academic literature about construction and urban regional data. With this information, we calculate the amount of material (material intensity) used in the construction area per $1m^2$ built in different types of residential buildings, the proportion of structural elements, and their component materials. Therefore, we normalize the categories of existing buildings based on case studies and extrapolate values for the sub-regions and the whole city. As the cities are heterogeneous with respect to land use and types of residential buildings, the first extrapolation to sub regions increase the accuracy of the study. A case study of the stock of residential buildings in the city of Rio de Janeiro aims to validate the method.

A flow scheme of the study is established in order to facilitate the process of comprehension of the building stock and estimation of its material flows. The flowchart of Fig. 3.1 illustrates the workflow of the study for application of the method for material flow analysis is of a building stock.

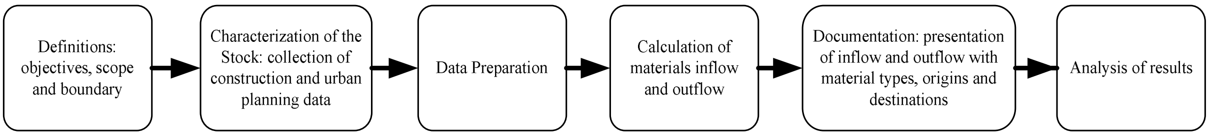

Fig. 3.1 - Study flow

3.3.1 Conceptual framework

In this study, the material flows are calculated between three stages: *Stock as in a baseline year*, *Use,* and *Demolition.* Where, *Stock as in a baseline year* is the stock as it was in 2010. *Use* corresponds to the remaining time of the buildings use, when there are material exchanges from the buildings maintenance until their end of life. *Demolition* represents the end of its life, when the buildings are dismantled; even if they have different mortality time. These phases are analyzed as *black boxes.* For each phase of the stock, we have identified:

- Input of materials and its sources;
- Output of materials and its destinations.

We model the material and waste flows and characterize it, considering:

- Number of buildings;
- Building types;
- Number of accommodations;
- Material intensity;
- Material input,
- Waste output;

- Time of mortality.

The geographic boundary is the city, in five sub regions. The temporal boundary is the stock use (from 2010) to its end-of-life.

For the flows calculations, we use indicators of material and waste during the phases: Material Intensity in Stock (MS), Material Intensity from Reposition (MR), Waste Intensity from Reposition (WR), and Waste Intensity in Demolition (WD). Since we disregard new buildings and extensions, the amount of material in stock remains constant until its demolition and all input of material is equal to all output of waste. The timeframe of buildings use is not ignored; this calculation is described after as *buildings mortality*.

Fig. 3.2 shows a conceptual scheme of the system.

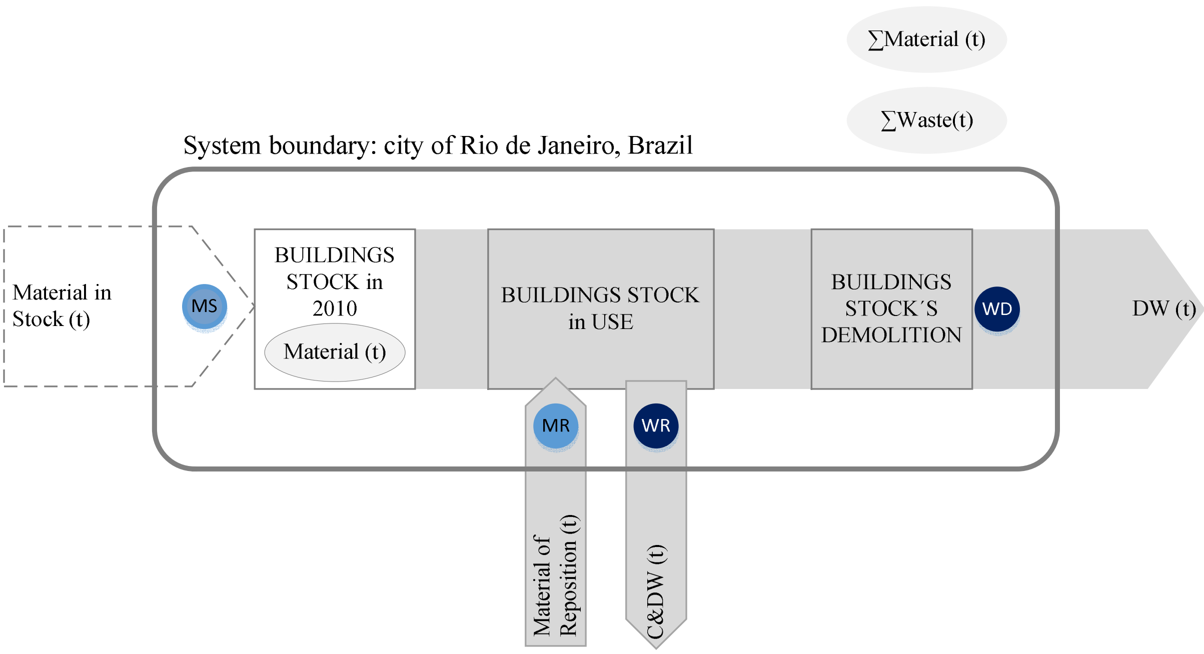

Fig. 3.2 - Conceptual scheme of the system and the variables of building stocks

3.3.1.1 Assumptions

The main premises of this study are:

1) The stock is constant: this method is not *dynamic* and does not consider new buildings during the period of use. For the prediction of new construction in an extended period, some economic, socioeconomic and housing Market analyses are necessary; they are not part of this study. We focused on analysis of construction and urban variables to identify and characterize the building stock.

2) Baseline of the year 2010: we adopted the year 2010 for the case study of the city of Rio de Janeiro because the later official statistics and the urban studies are not updated. The latest census is from 2010 [174] and we use this census to calculate the equivalent areas per family and per occupant. The changes in the city made in order to prepare the *Olympics games 2016* and their infrastructure were large and still are not documented. In addition, the law for waste management in Brazil from 2010 reflected in many uncertainty about the destinations and treatments of waste.

3.3.2. Characterization of the stock

The characterization of the building stock consist in identifying the construction and urban aspects that influence the stock and its behavior during the remaining time of use and in demolition:

- Analysis of representative buildings and its peculiarities, similarities; as: built-up area, used and consumed materials and waste generated;
- Identification of building types and its occupation in the city's sub-regions;
- Identification of the buildings age;
- Survey of total constructed area;
- Survey of buildings elements reposition; and
- Survey of construction and waste.

3.3.2.1 Construction variables

The construction variables are *Material Intensity* (MI), the *Ratio of Material Loss* (RML) and the *Lifetime* (LT).

To calculate the *Material Intensity* (for buildings and for its elements), we analyze four types of model buildings, which are representative of residential buildings, and extrapolated their MI to the sub-regions and the city, considering density studies of land use and urban diagnosis. The functional unit of $1m^2$ of constructed area is used. The *Material Intensity* for construction, demolition and expansions are derived from the above cited. Moreover, we analysed the *Material Intensity for this service* (MIPS) only focusing on the amount of material used for construction that also incorporate the material loss rates in construction. The calculation for MIPS is given by: $\mathrm{MIPS} = \mathrm{MI} \cdot (1 + \mathrm{RML})$.

Where, MIPS of construction = MI in buildings *(1+rate of Loss for the materials in construction)

The *Ratio of Material Loss* during constructions is delivered by national statistics.

For the *Lifetime* of buildings, we use 100 years, usually used in studies about buildings life cycle [175]. The lifetime of buildings elements is estimated based on standards (for buildings performance).

The estimation of *constructed area equivalent per family* and *per occupant* is achieved by division of areas of buildings by the number of families and the number of occupants in each home.

3.3.2.2 Urban variables

The urban variables are *Total Built Area* (TCA), *Total Demolished Area* (TDA), occupation density by types of buildings and the *Age* of buildings (AGE)

We estimate the urban variables from the analysis of urban studies and statistical data (licenses for construction, construction of waste collection). We estimate the ages of buildings by the comparison of archetypes, which are the characteristics of the buildings, with buildings types typical in the sub regions through an investigation of the urban development of the city. The remaining time of the buildings types are calculated by subtracting the ages of buildings of the expected time of life. Then, we could also predict the time for their mortality.

Fig. 3.3 illustrates characterization of the building stock, where the dashed shapes on the left represent the sources for survey and the shapes in continuous line on the right side represents desired survey.

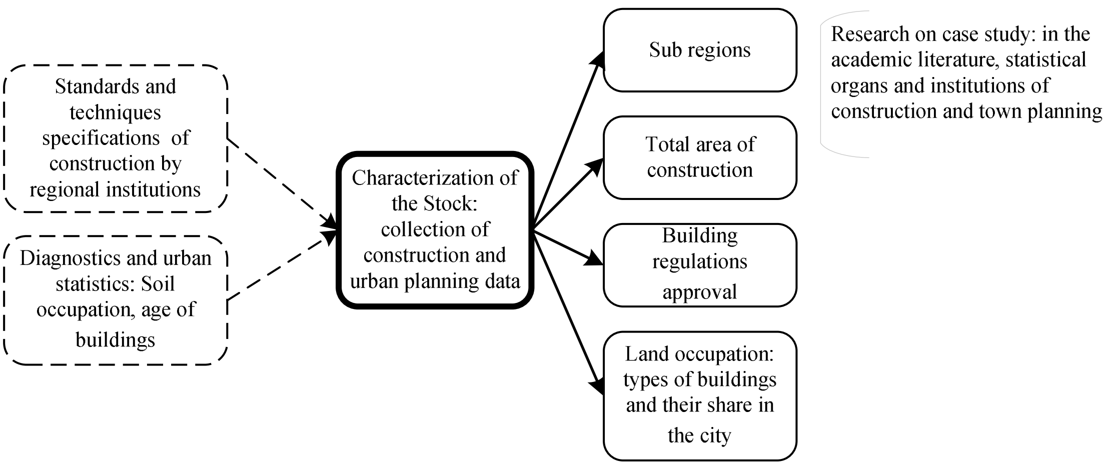

Fig. 3.3 - Diagram caractherization of the building stock

3.3.2.3 Data Preparation

These step concern in normalize the variables from statistical data for estimation of the stock and the material and waste flows. These calculations are specifics for this case study and are explained in detail in this section.

Fig. 3.4 shows the preparation of the data: in dashed balloons are the data and statistics we review in the literature and institutions, and the balloons on the right side represent steps concerning data preparation.

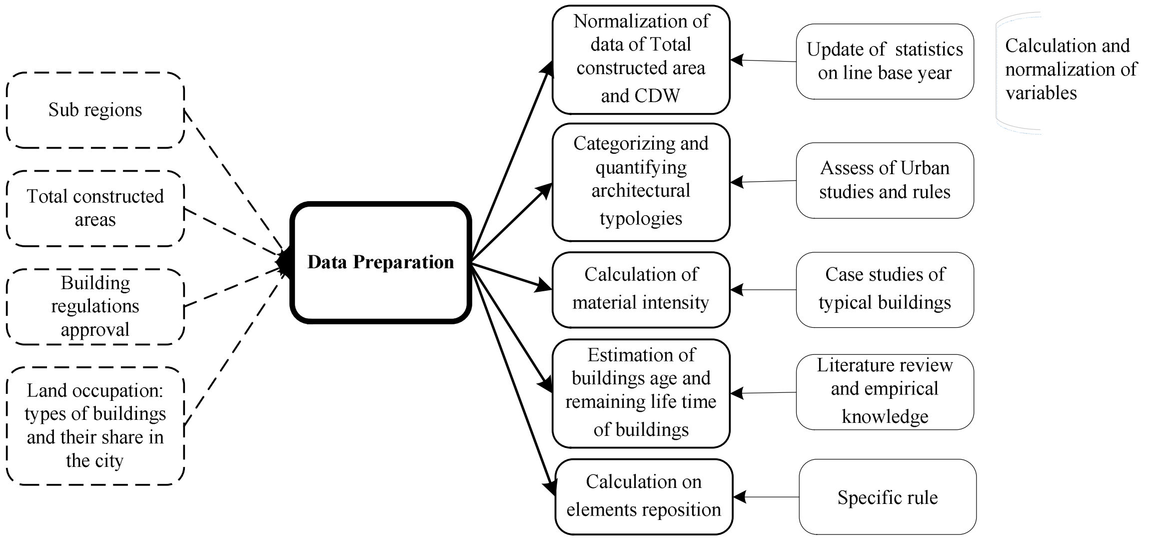

Fig. 3.4 - Diagram of data preparation

To calculate the inflows and outflows of materials above the system, we apply mathematical equations that consider the types of buildings, occupation (share of building types in sub-regions) and participation of sub-regions in the city. Fig. 3.5 shows a diagram of the calculation of inflow and outflow, where the normalized data are in dashed balloons and the exchange materials are indicated in the balloons on the right side.

We estimated the amount of material and waste from the lifetime of the project described in standard for the buildings performance. The material input and the generation of waste during the use phase are due to replacement of building elements for maintaining the *Use* phase. The waste generated in their *Demolition phase* is the mass of material in *Stock as in baseline year*.

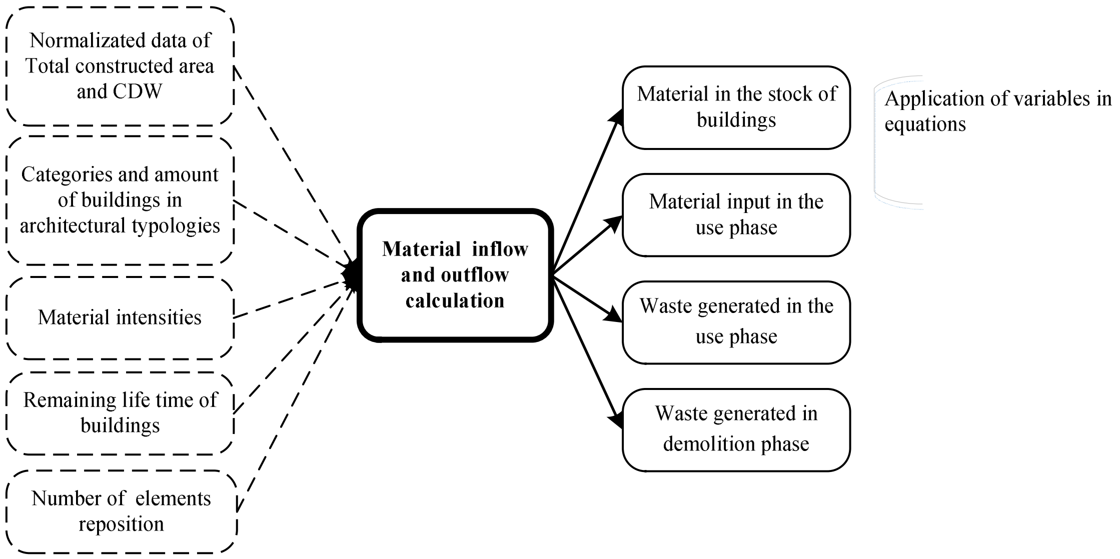

Fig. 3.5 - Diagram of calculation of inflow and outflow

According to the MFA precepts, we consider each material-component of the building stock to assume that:

- Mass of material in Stock = Material Intensity- Losses of material in construction site
- The sum of the mass of materials consumed in the whole system is equal to the mass of waste generated by the system until the end of life of the buildings (∑Material_ t´=∑Waste_ t´).
- The mass of material in stock in use on remaining lifetime is the mass of stock material in the base year plus the material used in replacement of building elements less waste generated in the stock use (M_t´ = SUM {t´|t´<=t} * (MS+MR_ t´-WU_t´).
- The mass of material in stock in the baseline year is equal to the mass of waste generated in demolition stock (MS=WD)
- t´= total remaining time, until the end of life of the buildings. The t' is inherent in the type of buildings and their ages; for calculation purposes, we use proportional rate of one useful life.

3.3.3 Indicators for calculation

3.3.3.1 Material in Stock in baseline year

For the calculation of materials in *Stock in the baseline year*, we set the *Material Intensity* for the construction of buildings in high occurrence categories in the city, considering the urban planning sub regions, which dictate the rules of construction, considering just ordinary buildings. Sub regions made up the city with their own characteristics, as differences in the types of residential buildings. We consider this difference the percentage of occurrence of the type of building in the sub regions of the city.

The mass of a certain material *m* in building stock of a sub region *s* is denoted by $MS_{m,d}$ in function of the building type *b* is given by Eq. 1:

$$MS_{m,s} = TCA_s \sum_b MI_{m,b} \cdot (1 - RML_{m,b}) \cdot LO_{b,s} \tag{1}$$

Where

TCAs = Total constructed area per sub region

MIm,b = Material intensity of certain material and certain building type

RMLm,b = Ratio of mass of material lost in the construction site (waste of material on site) (%)

LOb,s = Land occupation per buildings type and per sub region (%)

The mass of a certain material *m* in building stock of a city *c*, considering the building type *b* is denoted by $MS_{m,c}$, and given by the Eq. 2:

$$MSm,c = \sum_b MSm,s,b \tag{2}$$

Where,

MSm,s *mass of a certain material* in building stock of a subregion

MS *material intensity of the building stock (t)*

3.3.3.2 Material in Use phase

The mass of material used by building stock during the *Use phase MU* is given by the *Material Intensity* of the elements exchanged for maintenance of buildings *MR* added the material of new buildings *Mn* plus material of expansions *Mp*, considering the remaining time of their use t´, that is, the timeframe until their demolition.

$$MU_t{}' = MR\_t' + Mn\_t' + Mp\_t'$$

Where,

MU *material of use phase (t)*

MR *material intensity of replacement (t)*

Mn *material intensity of new buildings (t)*

Mp *material intensity of expansions (t)*

The scope of work is limited to the static stock disregard new constructions, then Mn = 0 and Mp=0, so $MU_t' =$The Number of replacements of building element *NRE* is given by dividing the remaining-time *RT* of the building for the life of the building *LTE*.

$$NR\_t' = \frac{RT}{LTE}$$

Once we do not find previous surveys on replacement of materials in use, we considered totally replaced and adopted REB= 1 (100%) of material at the end of the useful life of the building element.

The Remaining life span of stock *RT* is given by subtracting the age of the building *AGE* in the total life of the building *LTB*.

$$RT = (LTB - AGE)$$

Where we conclude that the number of replacements of building elements *NRE* is given by:

$$NRE\_t' = \frac{LTB - AGE}{LTE}$$

Where,

t´ *remaining lifetime (=RT) (years).*

LTB *building´s lifespan (years);*

AGE *age of building stock (years);*

LTE *building element´s lifespan (years).*

The mass of a certain material *m* is used in replacement of an element *e*, in a type of building *b*, considering the *s* sub-region, denoted by *MRm,s* is given by Eq.3:

$$MRm,s = TCAs \cdot \sum_{e} MIm,b \cdot \left[(REBe,b \cdot MSHm,e) \cdot \left(\frac{TLBb - AGEb}{TLE} \right) \right] \cdot LOb,s \tag{3}$$

Where,

TCAs = total constructed area per sub region (m^2)

MIm,b = material intensity of certain material in certain building type (t/m2);

REB = ratio of building element replacement (%)

MSH = share of certain material in certain building element (%)

MU = material intensity of use phase (t)

MR = material intensity of replacement (t)

LTB = building´s lifespan (years)

AGE = age of buildings (years)

LTE = lifetime of elements (years)

LO = land occupation; ratio of certain building element per certain building type (%)

m = material

b = building type

s = sub region

c = city

e = element of building

The mass of a certain material *m* used in replacement of an element *e*, in a building type *b*, considering the city *c*, denoted by *MRm,c* is given by Eq.4:

$$MRm = \sum_{s} (MRm,s) \tag{4}$$

Where,

MRm,s = material intensity of replacement per material and per sub region (t)

3.3.3.3 Waste use phase

According to the theoretical precepts, the waste generated by the stock in use (construction and demolition) in remaining time *WD_t´* is stated mathematically as,

WD_t´= [MS + (MR_t´) - (WR_t´)] + [(Mn_t´ (1-RML_t´)] + [Mp_t´ (1-RML_t´)]

Where,

MS = material in the stock in 2010

MR_t´ = material from replacement of buildings elements during the remaining time of use

WR_ t´ = waste generated in remaining time of use

Mn_t´ = materials from the new buildings during use phase

RML_t´ = rate of material loss in replacement of material considering the remaining time of use

Mp_ t´ = material used for expansions considering the remaining time of use

Given that *WR=MR (1- RML), Mn=0, Mp=0 and (MR_t´) = (WR_t´),* then *WD_t´=MS* and *WU_t´=MU_t´=MR_t´*

Where,

The waste from certain material m in the sub-region s in the use phase, denoted by *WUm,s* is given by Eq.5:

$$WUm,s = WRm,s = MRm,s \quad (5)$$

The waste from a certain material *m* is in city *c* in the use phase is denoted by *WUm,c* and is given by Eq.6:

$$WUm,c = WRm,c = MRm,c \quad (6)$$

Where,

MR = material intensity of replacement (t)

m = material, based on survey

3.3.3.4 Waste in demolition

Once the outflow material from the stock is equal to the inflow material from it, and that calculation ignores new constructions and expansions, then:

The mass of waste of a certain material *m* in the sub-region *s* in demolition, denoted by *WDm,s* is given by Eq.7 and the mass of waste a certain material *m* in the city *c* in demolition, denoted by *WDm,c* is given by Eq.8:

$$WDm, s = MUm, s = MSm, s \quad (7)$$

$$WDm, c = MUm, c = MSm, c \quad (8)$$

Where,

MU = material intensity of use phase (t)
MS = material intensity of the building stock (t)
WD = waste intensity from demolition (t)

3.3.4 Documentation and interpretation

A Sankey diagram illustrates the materials flows. Sankey diagram has been widely used for materials and energy flow analysis [95]. Charts of columns and lines show the results for *Material Intensity.* A *direct interaction graph model* illustrates the links between variables and indicators for calculation. A line chart shows the period for the mortality of Rio de Janeiro housing stock.

3.3.5 Analysis of results

In this stage of the study, we interpret the results for *material intensity, materials flows* and *land occupation* with a technical look and empirical knowledge.

3.4 Case study: the building stock at the city of Rio de Janeiro

3.4.1 Urban issues

The city of Rio de Janeiro is 99.5% urban [174] and considering new construction license data in the South between 2000 and 2004, it is estimated that 84.4% are residential new housing [176]. The city of Rio de Janeiro has 5 Urban Planning Areas (AP) and 33 Administrative Regions (RA) [177]. For greater fidelity in the estimation, we used sub regions of planning areas (AP) as an intermediate unit first and then we extrapolate the material intensity to the whole city.

The blueprint (named *Plano Diretor*) is the law that dictates standards and guidelines for the sustainable development of cities in many aspects of urban dictating rules to achieve health and prevent speculation in cities. Thus, the Rio de Janeiro´s *Plano Diretor* [178] aims to control the growth and regulation of the growth of cities, directly influencing the use and occupation of urban areas.

The range of residential buildings in stock at Rio de Janeiro is heterogeneous, with different types of buildings and urban occupation. The blueprint of the city of Rio de Janeiro, since the current rules was ratified in 2011 [179], that is, after our baseline year and did not have time to seriously impact on the actual stock of buildings. Therefore, the city of Rio de Janeiro was in 2010, and still is today, very heterogeneous about its land use. APs 1, 2 and 3 are dense with high buildings saturation, while AP4 is in development. AP1 is predominantly financial and commercial; AP2 comprises areas of upscale residential, tourist and commercial; AP3 includes residential and commercial areas; AP4 comprises a recent urbanization area in urban planning that favors the use of cars with high-rise apartment buildings into condominiums, new commercial and financial center; and AP5 comprise single-family houses, in areas with less favored in infrastructure.

The map based on Cardeman study [180] shown in Fig. 3.9 supports these findings and give more details about housing occupation.

The *Caixa Econômica Federal* (CEF) [181], which is the main federal institution of habitation funding in Brazil, categorizes urban typologies for housing in popular, residential house, detached residential house, residential building and residential building with pilotis[1]. On the other hand, the *Brazilian Association of Technical Standards* (ABNT) [182] and the construction unions in the country [183] follow the standard NBR12721[184]. The NBR12721 classifies residential buildings among 4 levels of single-family houses, and 8 levels of

[1] Piloti: “Usually in *plural*. Any of a series of columns or piles, typically used to raise a building or part of a building above ground level” [295].

multifamily buildings, in function of the number of apartment floors, the number of bedrooms and finishing standard.

Therefore, urban rates affect directly the building stock. The indices of total constructed area, occupation density, age of buildings, and building types aid us to create the building stock profile. Construction and Demolition Waste (CDW) rates give an overview about the flow of materials, treatment and disposal of waste.

The timeline in Fig. 3.6 shows, in a synthesized form, the evolution of the stock of residential buildings in Rio de Janeiro. There is no available data on homes removal and new construction in the last years. The map of the Fig. 3.9 illustrates the sub regions.

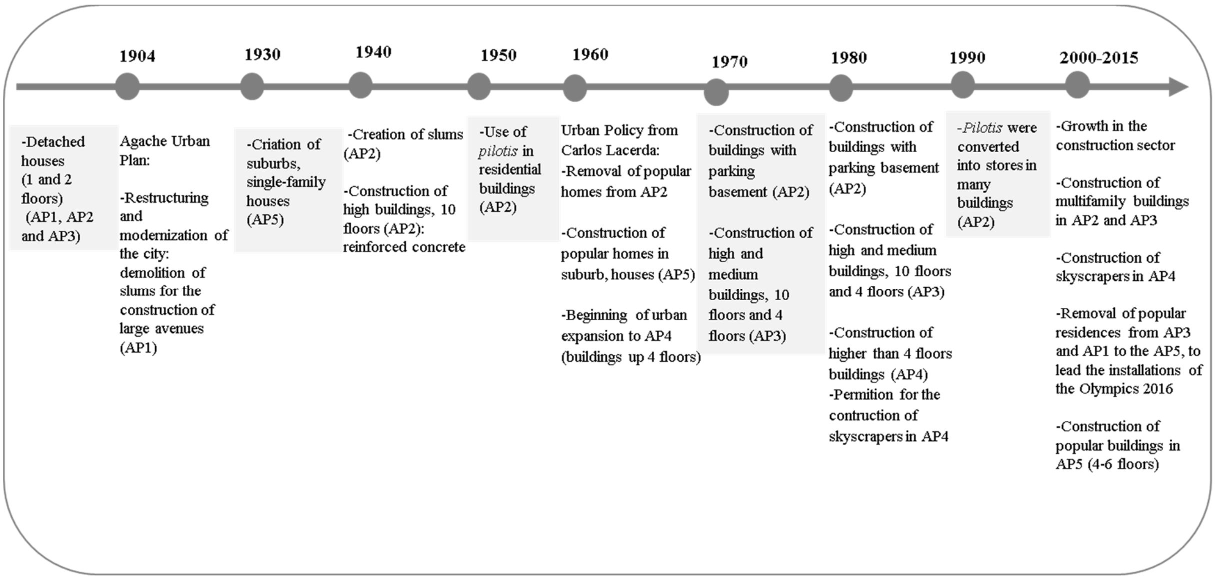

Fig. 3.6 - Timeline of urban evolution for residential buildings in Rio de Janeiro. Based on [180,185–188]

3.4.2 *Waste issues*

According to the classification of waste given by CONAMA [17], aggregates, ceramic and concrete can be recycled and reused for constructions of buildings and infrastructure; for that, these types of waste should be transported to recycling plants. Until 2010, waste from plastic, metal, glass and wood should be transported to *sorting plant* (ATT), where they should stay temporarily stored for recycling in the future. Studies about loss of construction material in site in Brazil show a lack of standard among the works in the same cities [189–191].

Considering the data of CDW collected in 2010 at the State of Rio de Janeiro, 59% are from renovations, expansions and demolitions, 20% from new housing and 21% from dwellings over 300m^2 [192]. Regarding the transportation of renewal, expansions and demolition waste, 9% is transported to *sorting plant* (ATT), 27% to *recycling plants* and 64% is transported to landfills [193], being 70% for *Gramacho landfill* and 30% for the *Gericinó landfill* [194].

Fig.3.7 shows the annual data, among the years 2007 and 2014, of waste collection at Southeast region of Brazil, region in which the city of Rio de Janeiro belongs, at for Brazil. The increase of collection in the region was proportional to the country. However, the lack of documentation prior to 2007 CDW hinders a broader historical analysis.

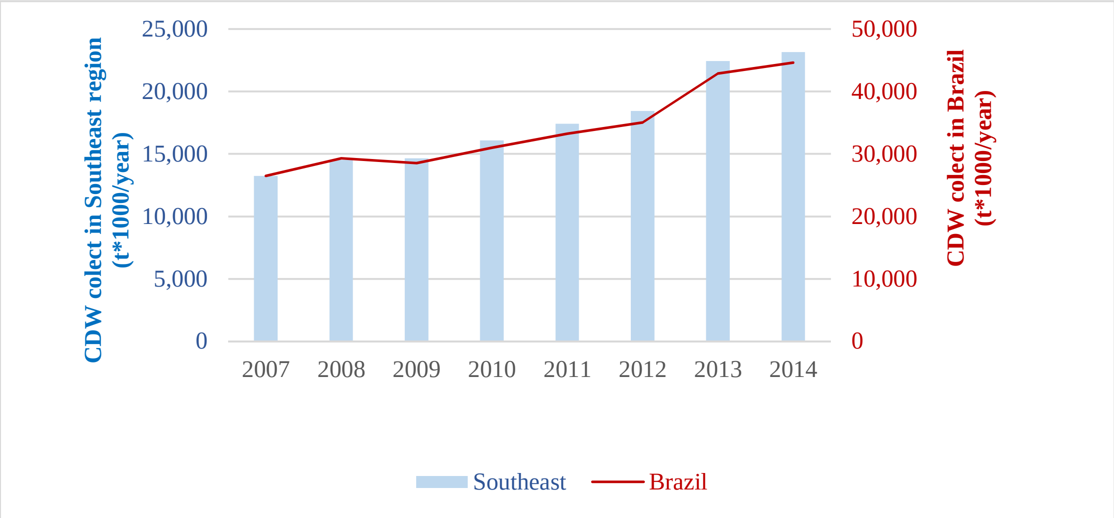

Fig. 3.7 - CDW colect between 2007 and 2014 [296]

3.4.3 Variables

3.4.3.1 Construction variables

The *Material Intensity* for Brazilian residential buildings and its elements are calculated from rates of material consumption in model type buildings described in TCPO guide [191]. TCPO presents national averages of material consumption during assembly or construction as demanded in Brazilian construction. This manual is widely used in this country for the elaboration of construction budgeting in the public and private sectors.

This study adopts *Lifetime* of buildings and its elements as described in the Brazilian series of performance standards for residential buildings NBR15575 [18,19], that is based on the British Standard BS 7453 [195], and in international literature [196–198]. The NBR 15575 series deals with the useful life of projects and categorizes building elements such as replaceable, susceptible to maintenance, and not susceptible to maintenance. The replaceable elements have shorter life than the building; they must be replaced between short intervals throughout the use of the buildings (such as floor coverings, tableware ceramics bathroom, and metal fittings). The elements susceptible to maintain are durable but require regular maintenance; they may be substituted between large intervals throughout the use phase of buildings (such as windows and facades coating). The elements that are not susceptible are the ones which and subject of maintenance have the same lifetime of the building, since they cannot be replaced (such as foundation and many structural elements).

3.4.3.1.1 Indicator of Material intensity and material intensity per service

The materials used during building construction (MIPS) and the MI are estimated based on analysis of case studies of buildings models, which are representative of typical residential buildings in Brazil. We consider national averages of material consumption and generation of construction waste. This study uses 1m^2 of constructed area as functional unit to calculate the building stock.

First we modelled hypothetical buildings, of which the Architecture follows the recommendations of the Brazilian standard NBR 12721: 2007 [184] and is used by *Regional syndicates of the construction industry in Brazil* (SINDUSCON) [183,199] as a base for calculations of *cost per unit of constructed area* (CUB/m²) [200]. Next, we use a budgeting method for construction budgeting to four model buildings to calculate the MIPS and MI. This method consists in reproduce the amount of materials used by building constructions using national averages of material consumption by service (described in *Manual of prices composition tables for budgets* (TCPO) [191]). The buildings modelling consist in promote basic designs of the main disciplines (foundation, structure, electrical, water and sewage facilities), with some technical assistances [201,202].

3.4.3.1.2 Model type buildings type

The model buildings include single-family houses (SFH) and multi-family buildings with four apartment floors (MFB-4F), with eight apartment floors (MFB-8F) and with 16 apartment floors (MFB-16F).

The architectural designs of buildings types follow recommendations from the Brazilian standards [184,203] , such as floor area, area of facade openings for ventilation and lighting and floor-ceiling height. The regular buildings were modelled with the same construction technology: a *slab-column-beam* structure, *clay hallow-brick* masonry walls, and paint or ceramic tiles as finishing walls [204]. Different from SFH, the multifamily buildings share the same floor plan, with four flats per floor. Table A3.1 and Table A3.2 show the technical specifications of the architectural designs and the occupancy of each model type. Even though the multi-family buildings have the same flat floor plan and general characteristics, they are different in non-residential areas and are not directly proportional. Unlike the others, MFB-4F is on *pilotis* and has no underground, and MFB-16F has a more extensive area for underground and ground floors than does MFB-8F.

The houses in slums are an important part of the stock of residential buildings in the city of Rio de Janeiro in urban aspects, physical and cultural. However, they are usually built without professional monitoring and tend to not have the safety requirements (structural safety, fire safety, safety in the use and operation), housing (tightness, thermal performance, acoustic performance, luminal performance, health, hygiene and air quality, functionality and accessibility, tactile and antropodynamic comfort) and sustainability (durability, maintainability and environmental impact) required by performance standard NBR15575. Therefore, the houses from slums are disregarded in this study.

We evaluated the architectural characteristics comparing the built areas equivalent for the whole buildings, for one occupant, for one family, and for parking space per family.

3.4.3.1.3 Construction waste: material loss of construction in site

Based on national averages [191], we adopted losses of building materials in the construction site of 5% for iron, steel and metals, 15% for plastics and 10% for other materials for calculation of the material in the buildings inventory.

3.4.3.2 Urban variables

Urban studies [180,186,187,205,206], Google tools [207,208] and empirical knowledge in architecture, urbanism and civil engineering are the basis for estimating the age of the stock of buildings.

TCA is measured by the license Building regulations approval, *Habite-se*, provided by the Municipal Secretary of Urban Planning (SMU) [209]. While the *Institute for Applied Economic Research-Ipea* [210], the *Funding Authority for Studies and Projects - Finep* [211] and the *Company information and professional development in construction PINI* [212] are institutions that conduct research and published on consumption and material waste in construction, is in its own survey, or technical and academic literature review. Moreover, we consulted the *Pereira Passos Institute* (IPP) [213], that is an institution linked to city government which realized many urban studies in Rio de Janeiro city, to recognize this building stock.

3.4.3.2.1 Total constructed area

This study estimated the residential TCA in 2010 based on updates by the construction license from the TCA in 2000. The literature does not describe the percentage of licenses granted to AP1, AP4 and AP5, so the average percentages of licenses granted to AP2 and AP3 against the stock of 2000 were used to fill these gaps of AP1, AP4 and AP5 sub-regions. Therefore, the construction area licensed for occupancy permit plus the initial stock subtracted from the demolition area, is the stock in 2010.

The normalization of residential TCA data is taken from the year 2000, plus the constructed area consented by *Habite-se* of the consequent year by 2010 [176].

Therefore, the residential building stock in 2010 is given by Eq. 9:

$$TCAr_{2010} = TCAr_{2000} + \sum_{2000}^{2010}(TCArN_i - TDAr) \tag{9}$$

The new *TCAr* is statistical data and *TDAr* is calculated through the division of residential CDW collected by MI average for 1m^2 of constructed area.

Where,

$TCAr_{2010}$ = total constructed area (m^2), based on regional survey;

TDA = total Demolished Area (m^2)

TCArN = total Constructed Area from residential buildings considering New buildings (m^2)

TDAr = total Demolished Area from residential buildings (m^2)

i = years between 2000 and 2010

3.4.3.2.2 Total demolished area

This study calculated the CDW collected in the city coming from residential buildings by deducting the statistical data for the State of Rio de Janeiro [214–217]. The calculation reflects the proportion of population living in the city [174] and the population living in the State (41%) on the mass of CDW generated from the State multiplied by the share on TCA. Thereby, the CDW collected in the city is given by the Eq.10:

$$CDWcity = Mass\ of\ CDW\ from\ the\ State * \left(population\ of\ \frac{city}{State}\right) = \tag{10}$$

The CDW collected in the sub-regions *CDWs* is given by the Eq. 1:

$$\begin{aligned} Mass\ of\ CDWs \\ &= Mass\ of\ CDWcity \cdot (TCA2000r \\ &+ area\ TCAr\ 2000to2010 - areaCDWr2000to2010) \end{aligned} \tag{11}$$

The demolished TCA is calculated by dividing the mass of CDW collected by the intensity of demolition material, where material is the intensity in the construction less material loses in the construction site. Discounting the proportion of irregular buildings of percentage of demolition (Eq. 12).

The total demolished area *TDA* is calculated by dividing mass of *CDW* collected by the intensity of demolition material, where material is the intensity in the construction less material loses in the construction site. Discounting the proportion of irregular buildings of percentage of demolition *SIB* [218] (Eq. 13).

$$TDA = \frac{CDWcollected}{MId} \tag{12}$$

$$MId = [MIc \cdot (1 - RML)] \cdot (1 - SIB) \tag{13}$$

Where,

CDWcollected = construction and demolition waste, statistical data

MId = material intensity of demolition

MIc = material intensity of construction

RML = rate of material loss

SIB = share of irregular buildings, statistical data

The analysis of annual variations of areas built between 2000 and 2010 in sub-regions highlighted reduced growth by 2004, with slight rise and fall in new areas constructed, with the exception of AP4, which emerged around 150% (Fig. 3.8).

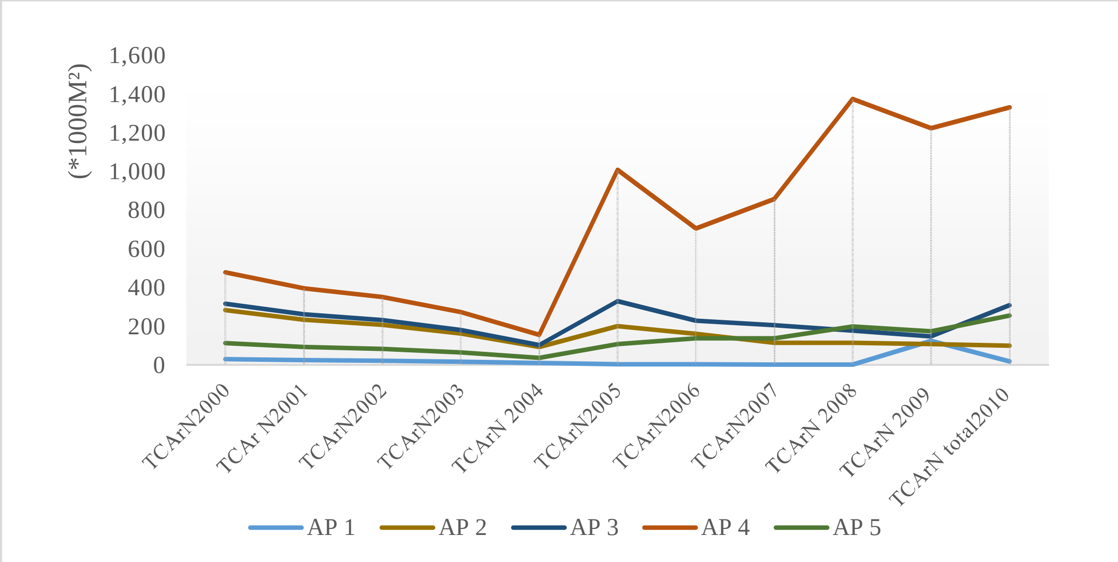

Fig. 3.8 - Graphical of new surface total constructed area of in the sub regions between 2000 and 2010

3.4.3.2.3 Building type and Occupation density of buildings

To estimate the occupancy rate of the model types of buildings (based on the buildings used in the calculation MI), we categorize the buildings by resemblance with each building type model suggested by Cardeman (map of Fig. 3.9 and Table 3.2). After vectorization of the areas indicated by Cardeman, we estimated the blueprint area from each building type model and multiplied by the average of floors, finding total built area. Being the density of building types represented by the average number of floors (1 floor in SFH, 5 floors in the MFB-4F, 10 floors in the MFB-8F, and 18 floors in the MFB-16F), we found the ratio of occupation of each building type in each sub region. Thereby, we found the proportions of building types in the sub-regions and in the city. In addition, the number of households of each building type was estimated. Despite the similarities of categories 2 and 9 are similar, we assumed the same building categories as the urban study [180]; that is, we kept them separated.

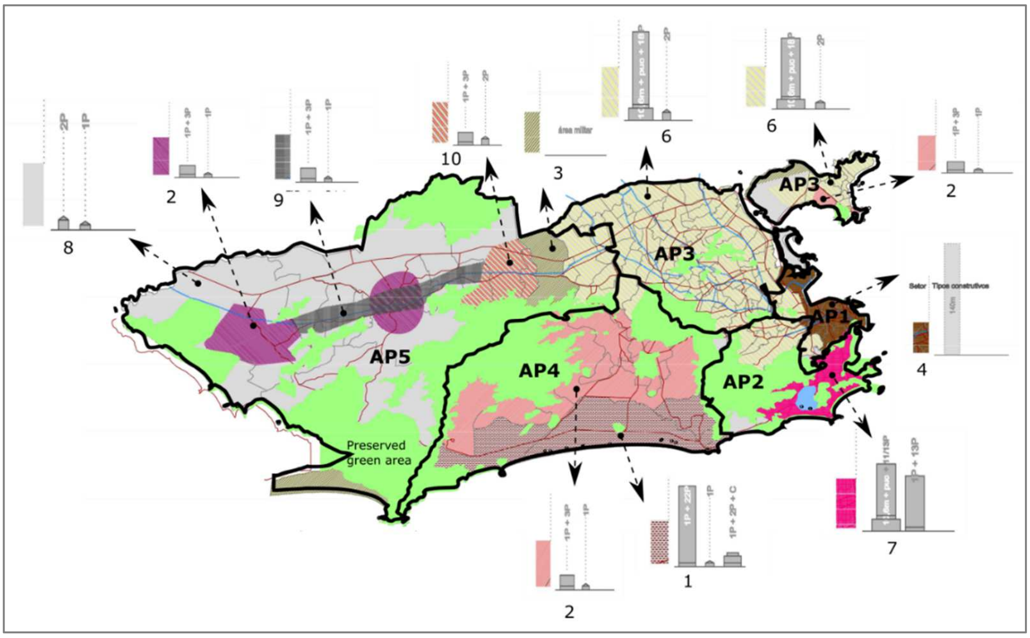

Fig. 3.9 - Occupation of building types and number of floor in the city of Rio de Janeiro. Based on [180,297]

Table 3.2 - Categories of building types

Categories	1	2	3	4	5	6	7	8	9	10
Types of buildings	1+22p	1+3	**	140m	1+3p	10.6m+puc+18p	10.6m+puc+11/13p	2p	1+3p	1+3p
	1p	1p	-	-	1p	2p	1+13p	1p	1p	2p
	1+3p*	-	-	-	-	-	-	-	-	-

* Considering coverage as a normal floor; ** military area

P:floor; PUC: common use floor

3.4.3.2.4 Age of buildings, buildings lifespan and lifetime of building element

We estimated the stock age from the analysis of architectural typologies through the comparison with the evolution of the stock of buildings in the city described by the urban study [180]. Based on the lifetime of 100 years for residential buildings and age of buildings (as exposed per the literature and empirical knowledge).

The evolution of the stock of residential buildings in Rio de Janeiro (Fig. 3.6) shows a start of construction of skyscrapers in AP2 in the 1980. In this decade and in the next one, there was a major economic recession and depression in the construction sector. It changed in the years early 2000s, as illustrated in the Fig. 3.8. Between 2004 and 2015 the construction sector was on the rise and many skyscrapers were built in AP2. We consider this trait to estimate the age of the skyscraper type buildings of this region.

Thereby, we estimated the following ages of building: 70 years for SFH, 60 years for MFB-4F, 40 years to MFB-8F, and 20 years for MFB-16F. Considering the lifetime of the estimates for each type of building and the occupancy rate and the age of similar buildings for each type studied, we predicted the stock mortality time 38% of the stock in 2040, 12% of the stock in 2050, 8% of the stock in 2070 and 42% of the stock in 2090.

3.5 Consolidated results

3.5.1 The stock

3.5.1.1 Characteristic from building type

This study considers the specific differences in architectural design of each building model type. MFB-4F is the only multi-family building that does not include underground parking and includes *pilotis* on the ground floor. The four types of buildings have a similar ratio between the private area of apartments and semi-public areas. On the other hand, SFH, MFB-4F and MFB-8F have parking for two cars per family while MFB-16F has parking for 1.25 cars per family. Both cases are similar in structure, wall type and linings; however, they differ in foundation, roof and water tank type.

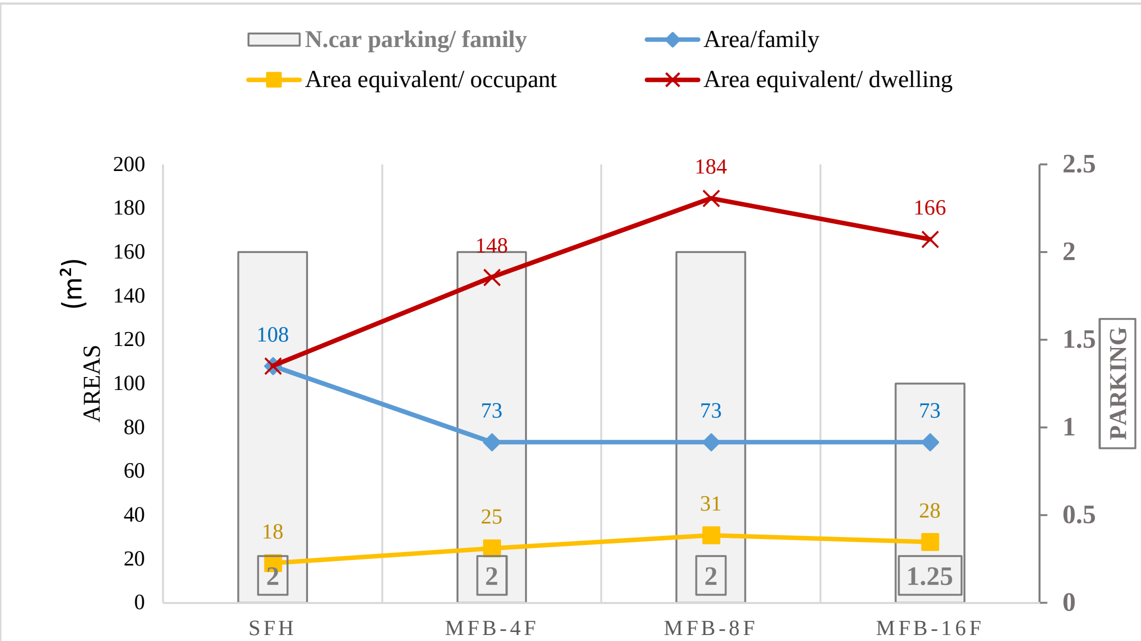

Fig. 3.10 – Case studies analysis

Fig. 3.10 shows the area per family, the area per occupant, the area equivalent per dwelling, and the number of parking spaces per family for the different building types. Even if the multi-family buildings are similar in terms of architectural plan, structure and wall systems and finish material, they have variables that distinguish them as unique and not completely comparable.

3.5.1.1.1 Building elements

The element structure, as expected, presents the most important contribution to the weight of all buildings types, as well as finishes mortar, especially in MFB-4F and MFB-8F. Facilities have insignificant contribution to the weight, and frames, stones, ceramic wares and metals do not reach 1% of the total building weight on their own.

3.5.1.1.2 Material input per buildings construction

Results show that the SFH weighs 2,580kg/m^2, MFB-4F weighs 1,004kg/m^2, MFB-8F weighs 884kg/m^2 and MFB-16F weighs 717kg/m^2. The mass of residues corresponds to the mass of material. Fig. 3.11 shows the ratio of materials contained in the building types.

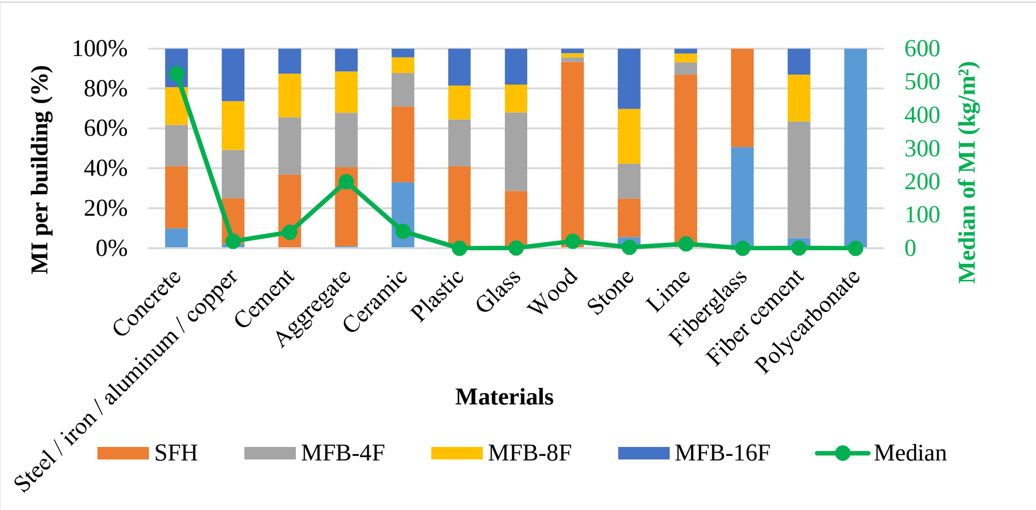

Fig. 3.11 - Ratio and median of material in tensity in building type

The multi-family buildings have wide consumption of concrete, metal, cement, aggregate, ceramics, glass, wood, cement and lime. The SFH has representative amount of plastic by use of water tank made of polyethylene, and wood from roof's structrure. In absolute terms, the median shows that concrete is by far the most representative material, followed by aggregates, ceramic and cement.

3.5.1.2 Material Intensity and Material Intensity per Service

Table 3.3 shows the MI and MIPS per material and per building found for 1m^2 constructed of the buildings types.

Table 3.3 - MI and MIPS from 1m^2 of buildings types

	SFH		MFB-4F		MFB-8F		MFB-16F	
Material	MI (kg/m²)	MIPS (kg/m²)	MI (kg/m²)	MIPS (kg/m²)	MI (kg/m²)	MIPS (kg/m²)	MI (kg/m²)	MIPS (kg/m²)
Concrete	845.29	929.82	557.91	613.70	511.60	562.76	524.75	577.23
Steel / iron / aluminum / copper	20.13	21.14	21.25	22.31	21.49	22.56	23.21	24.37
Cement	81.48	89.63	63.82	70.20	48.66	53.53	28.09	30.90
Aggregate	393.88	433.27	270.14	297.15	203.59	223.95	113.46	124.81
Ceramic	116.43	128.07	50.72	55.79	23.99	26.39	13.64	15.00
Plastic	0.54	0.62	0.31	0.36	0.23	0.26	0.24	0.28
Glass	0.80	0.88	1.10	1.21	0.39	0.43	0.50	0.55
Wood	868.96	955.86	20.64	22.70	20.09	22.10	21.16	23.28
Stone	2.46	2.71	2.23	2.45	3.50	3.85	3.87	4.26
Lime	28.29	31.12	19.73	21.70	14.11	15.52	7.91	8.70
Fiberglass	0.31	0.34	0.00	0.00	0.00	0.00	0.00	0.00
Fiber cement	0.00	0.00	3.40	3.74	1.37	1.51	0.76	0.84
Total	**2,358.57**	**2,593.45**	**1,011.26**	**1,111.33**	**849.03**	**932.86**	**737.60**	**810.20**

However, construction waste from materials such as brick, concrete and mortars are usually reused within the same building. Thus, it may be that the rates of material waste in construction for these materials are smaller. This can affect the MIPS of these materials in the construction. It is recommended that an inventory on this be done to minimize the uncertainty in this regard.

3.5.1.3 Interaction between variables and indicators

Fig. 3.12 shows the direct interaction between construction and urban planning variables and calculation indicators, where the connections indicate the dependency between them. MU depends on MS and MR; MS is connected with 3 variables; MR is connected with 14 variables; WU depends on MR and WR; WR is connected with 1 variable; and WD relies on MS and MR, and is connected with 5 variables. The largest number of dependencies of the indicators of the use phase with variables denotes a high complexity for their calculation, once we need to consider variables to forecast the lifetime of buildings and its elements.

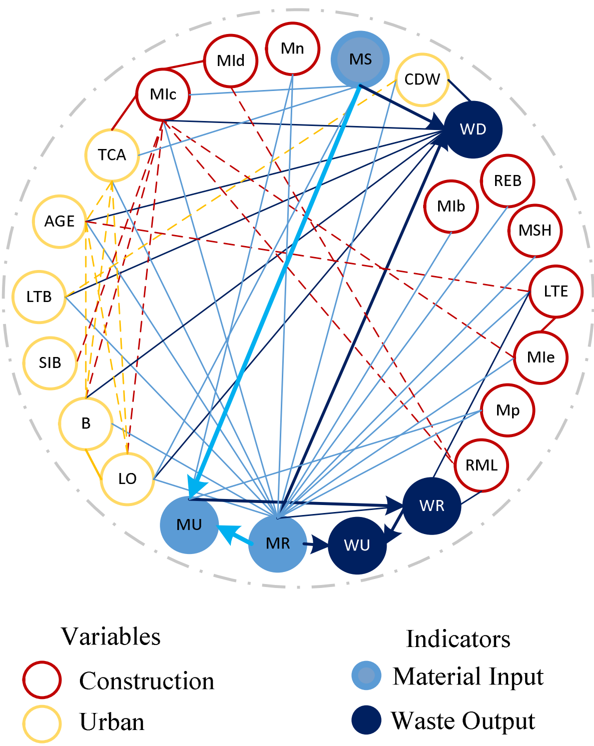

Fig. 3. 12 - Direct interaction graph model

Legend:
MS: Material intensity of the stock
MR: Material intensity of reposition
MU: Material intensity of use
WR: Waste generated from repositions of material
WD: Waste from Demolition.
WU: Waste from the Use phase.
LTB: Lifetime of building
LTE: Lifetime of element
MIb: Material intensity of building type
MIc: Material intensity of construction
MId: Material intensity of demolition
MIe: Material intensity of building element
MIp: Material intensity of expansions
RML: Ratio of material lost
TCA: Total constructed area
LTB: Lifetime of building
LTE: Lifetime of element
B: Typology of building
AGE: Age of buildings
LO: Land occupation
TDA: Total Demolished Area
CDW: Construction and demolition waste
SIB: Share of irregular buildings
MSH: share of certain material in certain building element

REB: Ratio of building element replacement

3.5.2 *Material flows*

The *Sankey diagram* of material flows from Fig. 3.13 illustrates the material flows in nodes in the stock of buildings in 2010, the use phase of buildings and demolition of buildings. Bearing in mind the direct source of the materials through the chain of construction industry supplies (industrial or nature), the mass of material in stock displaced in the use phase of buildings and after the demolition to the possible destinations areas. Considering the current scenario of construction and demolition waste treatment, the possible destinations areas are *sorting plant*, *recycling plant*, *Gramacho landfill* and *Gericinó landfill*.

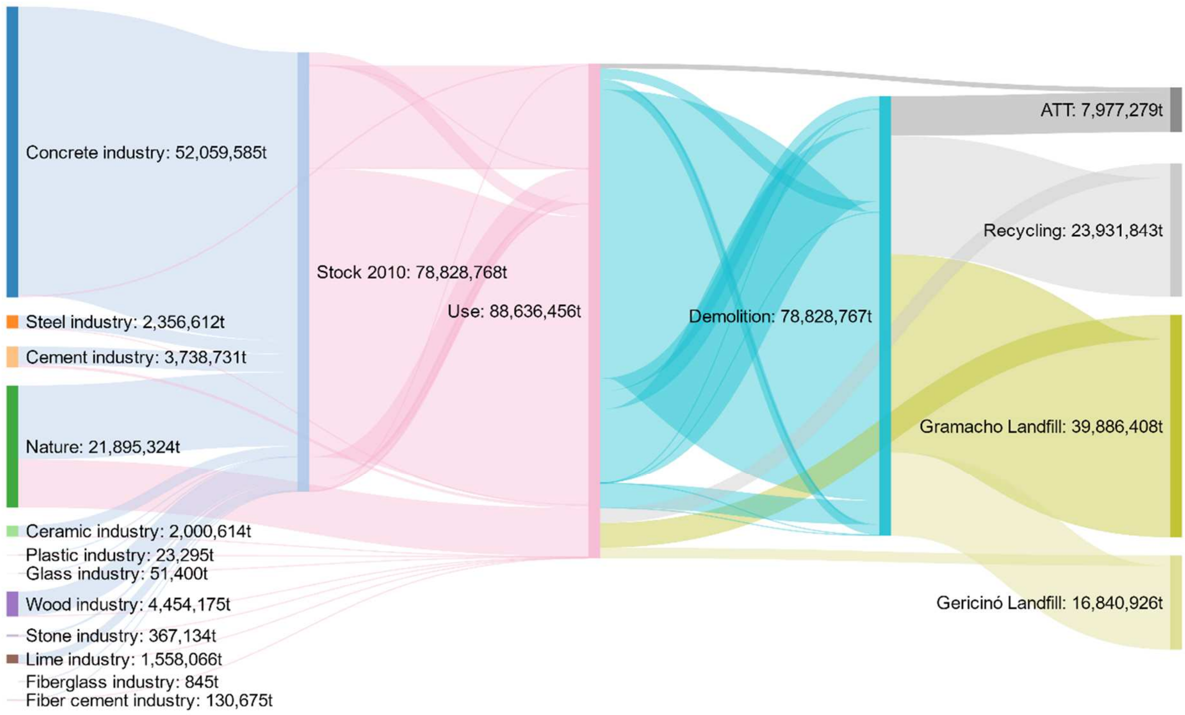

Fig. 3. 13 - Sankey diagram of material and waste flows of the lifecycle of the building stock of Rio de Janeiro city. Made in SankeyMATIC [219]

3.5.3 Mortality of building stock

Fig. 3.14 illustrates the evolution of the building stock mortality since the baseline year 2010 to its end of life.

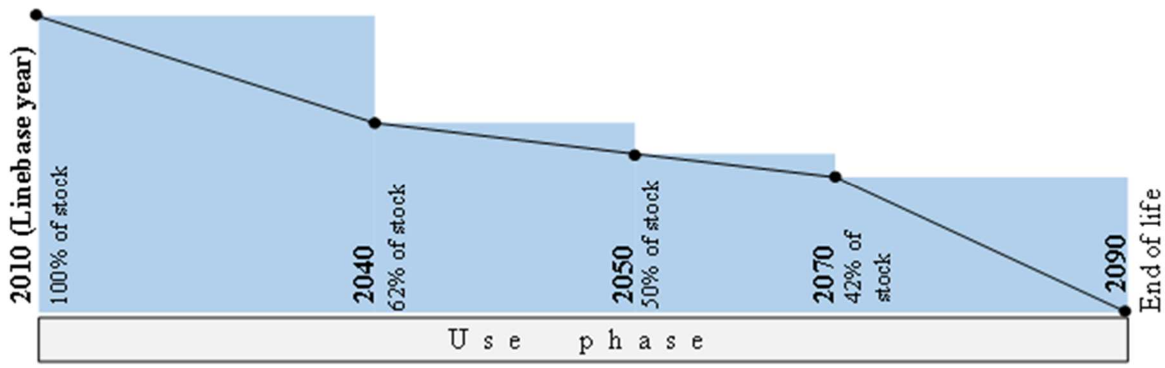

Fig. 3.14 – Time for mortality of building stock

Thereby, the building stock tends to reach the end of life gradually by the year 2090, unless measures of lifetime extension of buildings are take

3.6 Results analysis and discussion

The Fig. 3.8 of the new Building regulations approval (*Habite-se*) demonstrates large variations in the stock of buildings between city sub regions. The stability of the stock growth in the sub regions AP1 and AP2 highlights a saturation of stock in these areas. Since the city of Rio de Janeiro has a very heterogeneous building stock and different dynamics in their sub regions, it is appropriate for greater accuracy to evaluate the city considering first its regions separately.

Fig. 3.9 and Table 3.2 show that the AP1 and AP2 sub-regions have a high density of buildings (multi-family), AP4 has more multi-family buildings and low density AP3, and AP5 has predominance of single-family houses.

The AP4 that has been growing in recent years, with large residential and commercial buildings of high standard, and still has a great potential to growth. Analyzing the city occupation, we identify of saturation of sub-regions AP1 and AP3. However, the preparation of the city to receive the 2016 Olympic Games includes urban remodeling, with large residence removals in the noblest areas of the city (AP1 and AP2) to more distant areas from the economic and financial center (AP5 sub region). Thus, the event of the Olympics tends to accelerate the natural dynamics of the stock [185].

The *Material Intensity* from the building type, which is shown in Fig. 3.11, tends to undergo a change within a few years. The use of lime has been growing in buildings in recent years because new residential constructions in some regions of Brazil have been using plaster in ceiling finishes and of inner walls made of plasterboard. In addition, the use of structural concrete brick is increasing, not only in popular housing, but also in ordinary and high-end housing. Consequently, there is a tendency to reduce the use of ceramic brick and reinforced concrete structure.

Results of inflows and outflows of materials (Fig. 3.13) show that concrete is the most widely used material in the stock of buildings in the city of Rio de Janeiro. The concrete is present in the main structural elements, some of which (such as foundations and slabs) cannot be replaced in the use phase and consequently, can be an obstacle to increasing the lifetime of the buildings through retrofit. Elements such as beams and columns can be strengthened if there is wear and increased load demand. Therefore, the life of the concrete dictates the lifetime of the buildings. In the use phase, the materials used in coating (aggregate, plaster, cement and ceramic) have the dominant flow. Moreover, new *waste banks* [220] have been created as a tool for companies offer their CDW to exchange with other companies, focusing on reducing spending on transport. Statistical data about waste exchanges of between companies are not available yet. This practice can help to increase the sustainability in waste management.

3.6.1. Limitations and difficulties

A limitation of the study is its inability to predict material changes in atypical variables that can influence indirectly the stock. As demonstrated in Fig. 3.12, the survey of material flows during the use phase is complex because depends on many variables. There are peculiar variables that can influence in the material in building stock that can shorten or extend the buildings life expectancy, such as Real estate speculation, and tragedies, variations in the economy, lack of a proper maintenance and renovation, realization of retrofit. Retrofit is a renewal and modernization of buildings facilities, likely can extend the lifetime of buildings. Buildings retrofit is a new practice in the city of Rio de Janeiro, especially in residential buildings. There are no official data about it yet.

The main limitation of the study is that it does not analyses the variations on stock from new buildings. We choose to disregard material flows from new buildings because the lack of data. The last demography census is from 2010, and most urban studies of Rio de Janeiro are based on this census. Moreover, at the time of elaboration of this study, there was not recent data about construction license (not after 2012), and waste collection (not after 2013).

The lack of standardization in the documentation of statistical data is the main difficulties in the study of the building stock in the city of Rio de Janeiro. Mapping and constant control of vacant areas and construction of houses in slum areas would be of great value for the characterization of the city. In addition, the standardization of documentation may facilitates the work by employees within institutions, reduce the uncertainties from normalization of data for studies, and allow an easy exchange of information between institutions dealing with related topics.

Google Maps [207] and Google Earth [208] are not able to measure the buildings height in streets with high tree density, as are many of the Rio de Janeiro streets. Thus, the extrapolation of MI to TCA was more effective in estimating the materials in this case study. The Google tools served as supplemental investigative tools.

3.6.2. Comparison with other studies

We compared the case study results of the stock of buildings in the city of Rio de Janeiro with other studies that analyze stock of buildings in terms of types of buildings, the mass of buildings, intensity of materials for building area, estimated stock and potential waste generation. The analysis were based on the *National Survey studies per household samples - National Household Survey* (PNAD) [221] from IBGE, the *Construction industry unions* [183,199,222] and empirical knowledge in architecture, urbanism and civil engineering fields..

It may seem strange to compare a city of 1,200 km^2 to a country, 83,879 km^2 (Austria) [223], but there are similarities between these building stocks. The stock profile in Austria (in 2003) is predominantly single-family homes and bi-familiars as well as the stock of Rio de Janeiro (in 2010). However, in Rio de Janeiro, the dwellings in multi-family buildings are more numerous in accommodation. There is a great similarity in mass per area built (or materials-intensity) of the Single-family houses of Austria and Rio de Janeiro. Because of high population and housing density of Rio de Janeiro, the mass of material in its stock of buildings is incomparable to the Austrian stock. The lifetime estimated for stock in Austria (100 years) is the same as in the Rio de Janeiro. The estimation of potential waste generated annually for the stock in Austria is 1%, which seems to be a consistent with the Rio de Janeiro´s results.

This study compared the building stock at Rio de Janeiro with European ones, considering occupation of the city, concrete intensity in buildings and intensity of other minerals. Results show that the European stocks are composed of more low-density buildings, with higher consumption of concrete and other minerals in homes and lower consumption of these materials in multi-family buildings and skyscrapers. The main difference between multi-family buildings is the system inner walls, of which the buildings in Europe usually use gypsum plasters while in the Brazilians ones are made by brickwork and mortar are dominant.

3.7 Conclusion

This study estimated the stock of residential buildings in the city of Rio de Janeiro, the materials and their flows based on extrapolation categories of building types from analyzing five urban planning sub-regions. Using a *bottom-up* method, we characterizes the building stock through extrapolation of material intensity of 1 m^2 of constructed area to the total constructed area. Urban and construction indicators that interact directly on the stock are fundamental in the calculation of materials in stock in the base year during the use phase and demolition. By this means, the stock of residential buildings and the materials contained therein were found, and then, the material flows during the use phase and the demolition of buildings were estimated.

Results indicate that the stock of buildings at the city of Rio de Janeiro in the year 2010 has around 78,828,773t of materials in 73,756 buildings and 108,552,921 m^2 of total constructed area. This building stock shows a high number of accommodations in multi-family buildings, being 61,616 in Single-family houses, 5,446 in multifamily buildings and 6,694 in high-rise buildings. Considering the hypothesis that the buildings have lifespan of 100 years, we predicted the gradual death of the stock with peaks in years 2030, 2040, 2050, 2070 and 2090. This building stock tends to reset 9,807,694t of materials during the use phase. Concerning the waste generated during the use and demolition phases, according to the current situation of waste management in 2010, the *sorting plants* (ATT) should receive 7,977,282t of CDW, recycling plants should receive 23,931,846t, *Gramacho Landfill* should receive 39,886,410t and the *Gericinó Landfill* should receive 16,840,929t. Thus, the city still has a great potential in recycling CDW to be explored. Results verified that concrete is the material with highest material intensity of this building stock. The elements made of concrete cannot be replaced. Elements made with aggregates and timber are often replenished during the use phase. The MI of single-family houses in the city of Rio de Janeiro resembles MI of European residential buildings (close to 2.5t/m^2); however, the MI of concrete and other minerals is higher in Europe than in Brazilian buildings. The comparison between Rio de Janeiro, Europe and the specific case of Austria regarding materials intensity, population and number of buildings, shows that Rio de Janeiro has a more heterogeneous and dense building stock; which makes it much more complex to analyze than the European residential building stocks. Our analysis evaluates the residential building stock in the city of Rio de Janeiro, provides the amount of materials in it and used during its use phase, its profile about type and amount of dwellings, and their materials and waste flows. In addition, it predicted future peak of building stock mortality that will increase waste streams and predate a great demand for building materials.

The main contribution of this study is to propose a method for building stock estimation, considering its characteristics and material, which validated through the case study of Rio de Janeiro. Moreover, we promote a knowledge about the stock and the prediction of buildings mortality and potential of waste generation. It should help construction companies, transportation, recycling, planning the management of this residue and the construction of new buildings; and help the government to develop strategies for better use of building materials and management of construction and demolition waste during these transitions stages, aiming achieve sustainably. Future studies should consider sustainable indicators to assess the effect of material flows from residential building stock on the environment.

3.8 Nomenclature

3.8.1 Abbreviations

CDW	*Construction and Demolition Waste*
DW	*Demolition waste*
ATT	*Sorting plant*
TCPO	*Prices composition tables for budgets (the Brazilian manual)*
SINDUSCON	*Syndicates of construction industry*
CEF	*Caixa Economica Federal, Brazilian bank financing for housing construction*
CP	*Popular house (from “casa popular”)*
CR	*Single family house (from “casa residencial”)*
CR (G)	*Residential house in twin-home type (from “casa residencial geminada”)*
PR	*Residential multifamiliar building (from “predio residencial”)*
PR (P)	*Residential building with pilotis (from “predio residencial com piloti”)*
SFH	*Single Family House*
MFB-4F	*Multifamily Building with 4 floors of apartment*
MFB-8F	*Multifamily Building with 8 floors of apartment*
MFB-16F	*Multifamily Building with 16 floors of apartment*
MI	*Material intensity*
∑Material	*Summation material input during the stock´s life cycle*
∑Waste	*Summation of waste output during the stock´s use and demolition*

3.8.2 Equations

3.8.2.1 Indicators

MS	*Material intensity of the stock*
MR	*Material intensity of reposition*

MU	*Material intensity of use*
WR	*Waste generated from repositions of material*
WD	*Waste from Demolition.*
WU	*Waste from Use phase.*

3.8.2.2 Variables

3.8.2.2.1 Construction

LTB	*Lifetime of building*
LTE	*Lifetime of element*
MIb	*Material intensity of building type*
MIc	*Material intensity of construction*
MId	*Material intensity of demolition*
MIe	*Material intensity of building element*
Mp	*Material intensity of expansions*
Mn	*Material intensity of new buildings*
REB	*Rratio of building element replacement*
MSH	*Share of certain material in certain building element*

3.8.2.2.2 Urban

RML	*Ratio of material lost*
TCA	*Total constructed area*
LTB	*Lifetime of building*
LTE	*Lifetime of element*
B	*Typology of building*
AGE	*Age of buildings*
LO	*Land occupation*
TDA	*Total Demolished Area*
TCArN	*Total Constructed Area from residential buildings considering new buildings*
TCAr2010	*Total Constructed Area from residential buildings in the baseline year (2010)*
TDAr	*Total Demolished Area from residential buildings*
CDWcollected	*Construction and demolition waste collected, statistical data*
SIB	*Share of irregular buildings, statistical data*

3.8.2.3 Indices

s	*Sub region*
c	*City*
b	*Building type*
m	*Material*
e	*Element of building*
r	*Residential*
t´	*Time (until the end of the expected time)*

4. MATERIAL FLOW ANALYSIS COMBINED WITH LIFE CYCLE IMPACT ASSESSMENT FOR THE EVALUATION OF WASTE FLOWS FROM THE BUILDING STOCK

4.1. Introduction

Human development needs to be in balance with available natural resources. In recent decades, scientists have proved that, for the development of human activities, more natural resources will be exploited causing depletion [224,225] and climate change [226]. As a consequence numerous impact mitigation plans were created in order to facilitate the recovery of the environment deteriorated.

The solutions found by scientists and Governments to curb the impacts of development of human activities, were the dematerialization and decarbonization of economies. For the dematerialization, many countries require an efficient use of resources [40,45,46,227] by the optimization of the separation, transport and treatment of waste, which requires adjustments in resource and waste management [228–230]. While, for the decarbonization, there is a mutual effort among Nations to reduce greenhouse gas emissions (GHG) mainly on sectors of industry [231], energy [232,233], and transportation [234,235], and by reducing of resource consumption and waste generation [236].

4.1.1. Motivation

The increase in population and the demand for housing, plus the growth in the construction sector in Brazil, resulted in an increase of waste being generated. By the year 2000, most of the construction waste was dumped in inappropriate places ("*bota-fora*") therefore, consequently, not only causes pollution also causes severe flooding in the months of heavy rain, by blocking storm water drains. With the increase of waste generation, this scenario has become unsustainable and the National Waste Policy (PNRS) was created to support new scenarios for waste management in Brazil.

In addition, Brazil has plans, that includes the energy and transport sectors [236,237], to reduce emissions and mitigate their damage progressively. The peak being between 2030 and 2050. The PNRS and municipal regulations were created and designed to hold the responsible accountable and instruct them in the waste management and disposal [16,238–242]. In addition, specifically in the city of Rio de Janeiro, the municipal waste management plan suggests the preparation of solid waste inventory, environmental impact assessment, and the analysis and evaluation of the Product's life cycle, as some for the tools of integrated solid waste management [242].

The main objective of this study is to analyze the waste streams from the stock of residential buildings of the city of Rio de Janeiro.

The secondary objectives of this study are:

- To present the system: characteristics of the stock, amount of construction waste generated by the study during use and demolition;
- To develop an adequate methodology;
- To submit the inventory of stock found in the previous chapter in a consolidated manner to model the waste streams;
- To evaluate life-cycle impacts of waste streams and impacts by sensitivity analysis
- To interpret and discuss the results; and
- To suggest additional measures to the national solid waste policy (PNRS) and the waste management plan of the city of Rio de Janeiro.

The purpose of this study is to be a tool in the management of construction and demolition waste (CWD) in the city of Rio de Janeiro.

4.2. The system

The system analyzed includes the flows and treatments of the waste generated by the residential building stock of the city of Rio de Janeiro. This building stock and its waste were estimated by the material intensity extrapolation method, based on Material Flow Analysis, described in the previous chapter. This study disregards dynamics related to extensions and new buildings, therefore, the mass of material in buildings is the same of the waste generated by them. The resulting inventory for the building stock and the inputs of waste, which were calculated in the chapter 3, is described in Table 4.1.

Table 4.1 - Inventory data of the building stock and its inputs per functional unit from 2010 to 2090, based on the previous chapter

System	Residential building Stock		
Boundary	City of Rio de Janeiro, Brazil, years of 2010		
Subsystem	Five planning areas (sub regions AP)		
Function unit	Residential buildings		Amount
Detached houses	Single Family House (SFH)		61,616
Multifamily buildings	Multifamily buildings with 4 floors of apartment (MFB-4F)		3,525
Multifamily buildings	Multifamily buildings with 8 floors of apartment (MFB-8F)		1,921
High-rise buildings	Multifamily buildings with 16 floors of apartment (MFB-16F)		6,694
Age and remaining time life, considering lifespan of 100 years		Age in 2010 (years)	Remaining time (years)
SFH		70	30
MFB-4F		60	40
MFB-8F		40	60
MFB-16F		20	80
Waste generation annual potential			
SFH			0.2%
MFB-4F			0.4%
MFB-8F			0.3%
MFB-16F			0.1%
Total constructed area (TCA)		Ratio per sub region	Area (m²)
In AP1		5%	4,899,889
In AP2		33%	37,300,014
In AP3		31%	33,588,559
In AP4		19%	19,976,568
In AP5		13%	11,947,923
In the city		100%	107,712,953
Phases	Use (from 2010 until their end of life) Demolition		
Total waste input of:			Amount (kg)
Concrete			52,059,586
Reinforced steel			2,356,613
Cement			3,738,732
Aggregates			21,895,326
Ceramic			2,000,615
Waste input during the phases from:		Amount during use (kg)	Amount in demolition (kg)
Concrete		310,665	51,748,921
Reinforced steel		19,625	2,336,989
Cement		503,600	3,235,132
Aggregates		8,659,189	13,236,137
Ceramic		116,495	1,884,120

The previous inventory, in the chapter 3, predicted a as-in-2010 building stock mortality time of 38% of the stock in 2040, 11% of the stock in 2050, 8% of the stock in 2070 and 42% of the stock in 2090.

4.3. Methods

4.3.1 MFA combined with LCA

MFA has been used combined with LCA in order to evaluate flows and impacts of industry, buildings, construction sector, cities and countries (urban metabolisms) focus to provide data to enable improvements in the environmental loads of these different sectors.

The Table 4.2 presents the main characteristics of publications using MFA combined with LCA. As stated in these studies, MFA combined to LCA have been used to evaluate different sectors and scales at least since the end of the 1990s. In addition, MFA-LCA also has been combined with other methods to enlarge the scope of the analysis.

Table 4.2 – Literature review of studies using MFA and LCA combined [136,137,243–247]

Authors	Turner et al.	Lopes Silva et al.	Rincón et al	Rochat et al.	Ulhasanah et al.	Venkatesh et al.	Burström and Brandt
Year of publications	2016	2015	2013	2013	2012	2009	1997
What they analyze/do	solid waste management in National level	Material flows and a campus of university	MIPS and power consumption during operation of buildings considering different systems of facades of experimental buildings	scenarios about streams from polyethylene terephthalate (PET)	cement industry	the national stocks of concrete, steel, polyvinyl chloride (PVC) and pipelines	regional and local materials management; particularly, processes for biodegradable waste incineration and recycling
Locals of case study	Wales, in the United Kingdom	Catalonia region and a campus of the University in this region, Spain	Catalonia region, Spain	Colombia	Indonesia	Oslo, Norway	City of Stockholm, Sweden
MFA was used to	analyze the waste mass flows	assess material flows in macro level (Catalonia region)	evaluate the ecological footprint of materials	analyze the material and energy balance	analyze the material flows within the industry	inventory the stocks and flows	analyze of substances, using the static method ORWARE model (ORganic WAste REsearch)
LCA was used to	assess their GHG impacts.	analyze environmental impacts in micro levels (university)	assess impacts of the power consumption during operation of buildings	evaluate multiple environmental impacts	evaluate potential impacts from CO_2 emissions of production processes	analyze impacts	analyze environmental impacts
Method of LCIA used	GWP, 100 year	ReCiPe2008 method	the damage oriented indicator (Eco Indicator 99-EI99)	Eco-indicator 99, CML 2002, Impact 2002+ and the Colombian "Ecopoints Puntos de Impacto Ambiental"	Not provided by the author	CML2002	damage oriented (Eco Indicator 99-EI99)
Other method	N/A	N/A	N/A	Multi attribute utility theory (MAUT): used to evaluate other aspects along with the ones in the ecological assessment.	Material flow cost accounting (MFCA): used to calculate the costs of production and output control (waste and emission).	N/A	N/A
Objectives	to support solid waste management decision making	to compare impacts on macro and micro level	to compare the facade systems, considering theis ecological rucksack and energy consumption	to analyze scenarios about streams from polyethylene terephthalate (PET)	to propose the new system design of cement production as a preliminary design of eco-city	to discovery environmental impacts associated with the manufacture, installation, operation, maintenance, rehabilitation, and retirement of the pipelines phases.	to survey information to help the formulation of waste policies
Key words	Life cycle assessment Decision support Greenhouse gas emissions Material flow analysis Solid waste management	Hotspots Industrial ecology Service metabolism Service polygon	Building façade Constructive system Environmental impact LCA MFA	Life cycle assessment, LCA Material flow analysis, MFA Multiattribute utility theory, MAUT	Not provided by the author	Concrete greenhouse gas Emissions industrial ecology Life cycle assessment Material flow analysis Polyvinyl chloride Supplementary	Municipal waste management Organic waste Static modelling Material flow accounting Life cycle assessment Nutrient recycling Energy Environmental impact

4.3.2 Methods description

The waste flows of the building stock were analyzed using Material Flow Analysis (MFA) combined with Life Cycle Assessment (LCA). In this study, MFA was used to survey, model and analyzes flows, while LCA was used to assess life cycle impacts. As suggested by the standard ISO 14040 [30] and ISO 14044 [131], LCA is usually performed on four stages: goal and objectives, inventory, impacts assessment and interpretation. This study performs the inventory using MFA and the lifecycle impact assessment following the standard procedure; we calculate the impacts using the most appropriate dataset to this system created from the international LCA database EcoInvent [248]. The Fig. 4.1 shows the study flows.

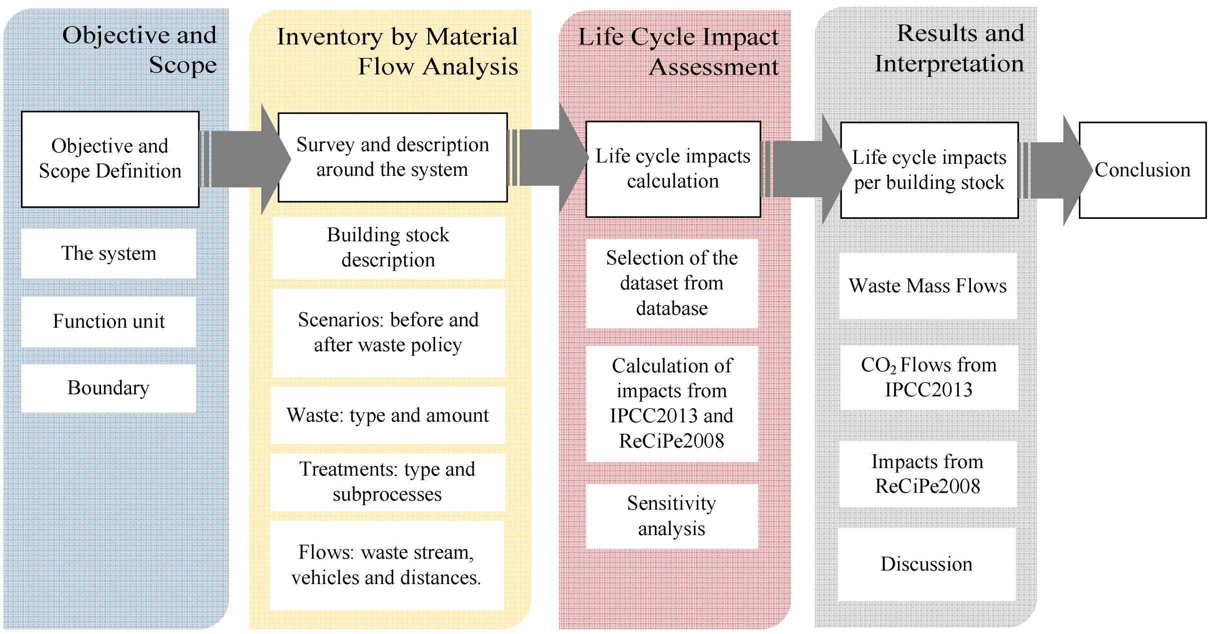

Fig. 4.1 - Study flow

4.3.3. Goal and scope

This research aims to evaluate the life cycle impacts of construction and demolition waste flows for the residential building stock in a city by following the IPCC2013 [249] and Recipe2008 [250] Impact Assessment Methods. We evaluate the impacts of the system from the phase of *Use* of the buildings from 2010 until their *End of Life* considering the final destinations, type of treatments, flows, and reuse of waste originated from concrete, cement, aggregates, reinforced steel and ceramic generated from use and demolition of the buildings.

4.3.3.1. Functional unit

The functional unit that performs the measurement and allows comparing different systems corresponds to the total constructed area of 107,712,953 m^2 in residential buildings, distributed heterogeneously in five sub regions of planning area (AP) and 1kg of waste.

4.3.3.2. Boundary

The boundary of this study covers the processes for waste treatment and transportation of the waste generated during the remaining time of buildings use and in their demolition, a remaining lifetime between 2010 and 2090.

4.3.4. Inventory by Material Flow Analysis

The scenarios of waste flows modeled were based on the interpretation and analysis of standards, statistical data, and technical and academic literature. These scenarios consider the changes caused by the new policy of waste [16]. Similarly, the inventory of vehicles and distances traveled by transport was made from interpretation of standards and technical and academic literatures. The inventory was performed by using Material Flow Analysis methodology applied to the city under the grey box concept, simplifying the system omitting sub processes.

Initially, scenarios ware created, as before and after the implementation of the National Policy of Solid Waste [16]. Next, rates of recycling were identified, considering the specific policy and contaminations rates described on the literature. The waste in the scenarios ware calculated, as described in the calculation procedures. Finally, treatments and destinations were surveyed in reports published by institutions and the flows were modeled. For modelling flows, the distances between buildings, intermediary destiny and final destiny were measured with Google Maps [207], using reference points by latitude and longitude coordinates system considering weighted averages for sub regions more intensity built area.

4.3.4.1. Calculation Procedures

For the calculation of the amount of waste generation in the scenarios, this study used the following equations.

The mass of waste W generated at the city c during the first stage of use q (between 2010 and 2013), denoted by $W_{c,q}$, is given by the Eq. 14:

$$W_{c,q} = \sum_{s,b} W_{s,b,q} \tag{14}$$

Where, $W_{s,q,b}$ is the mass of waste W generated at the sub regions s during the first stage of use q.

The mass of waste W generated during the first stage of use q (between 2010 and 2013), considering the sub regions s, denoted by $W_{s,q}$ is given by the Eq.15:

$$W_{s,q} = \sum_{b} W_{s,q,b} \tag{15}$$

Where, $W_{s,q,b}$ is the mass of waste generated by each building type b during the first stage of use q, considering the sub regions s.

Being, the waste W generated during the first stage of use q (years between 2010 and 2013), considering the sub region s and the type of building b, considering the land occupation, denominated by $W_{s,q}$, is given by the Eq. 16:

$$W_{s,q} = \sum_{b} \left(WU \cdot PW_b \cdot LO_{b,s} \right) \tag{16}$$

Where, WU is the total waste generated during the use phase, PW_b is the potential of waste per building type and $LO_{b,s}$ is the share of land occupation of the buildings type b at the sub region s.

The potential rate of waste generation per year was calculated in the previous chapter in function of building materials in use in buildings, and found 0.2% for the single Family house, 0.4% for the multifamily built with 4 floors of apartments, 0.3% for the multifamily built with 8 floors of apartments and 0.1% for the multifamily built with 16 floors of apartments.

In addition, the potential of waste generation for building type between 2010 and 2013, denoted by $PW_{b,m}$ is given by the Eq. 17:

$$PW_{b,q} = y \cdot PW_{b,y} \tag{17}$$

Where, y is the number of years of buildings use and $PW_{b,y}$ is the potential of waste generation per building type in this number of years of buildings use.

Also, the share of occupation from total constructed area (TCA) that was calculated in the previous chapter (Table 4.3):

Table 4.3 - Share of sub region in TCA of the city

Sub region / city	SFH	MFB-4F	MFB-8F	MFB-16F
AP1	11%	13%	2%	73%
AP2	0%	0%	1%	99%
AP3	1%	0%	34%	65%
AP4	6%	1%	0%	93%
AP5	6%	38%	0%	56%
RJ	30%	12%	0%	58%

Waste generated during the second stage of use *n* (years from 2014 to end of life), considering the sub regions *s*, denoted by *Ws*,*n*, is given by the Eq. 18:

$$W_{s,n} = WU_s \cdot PW_{b,n} \cdot LO_b \tag{18}$$

Where, *WUs* is the mass of waste generated during the second stage of use of buildings *n* in the sub regions *s*, and PW_b is the potential of waste generation for building type between 2014 and their end of life and the share of land occupation LO.

4.3.5. Life Cycle Impact Assessment

This study uses the IPCC2013 and ReCiPe2008 methods for the assessment of the following life cycle impacts: global warming potential for 100 years (GWP) from CO_2 equivalent emissions by IPCC2013 and climate change potential for GWP100yr (CC), fossil depletion potential (FDP), human toxicity potential (HTPinf), metal depletion potential (MDP), natural land transformation potential (NLTP), ozone depletion potential (ODPinf), urban land occupation potential (ULOP) and water depletion potential (WDP) from ReCiPe2008 [250] on the midpoint level of the *Hierarchist* model, which is considered a default model for scientific studies [251].

4.3.5.1. IPCC2013

The IPCC method assesses the global warming potential (GWP) from the greenhouse gases (GHG) emission from the system. Table 4.4 shows the GHG for 100 years, as settled down by the Kyoto protocol [252], which defines the amount of each gas has potential for global warming as equivalent to Carbon dioxide (CO_2) and consequently is equal to 1 unit measure of GWP (CO_2eq).

Table 4.4 - Emission of GHG equivalents to 1 CO_2eq, for 100 years [253,254].

Species	Chemical formula	Global Warming Potential (Time Horizon) for 100 years
CO_2	CO_2	1
Methane *	CH_4	21
Nitrous oxide	N_2O	310
HFC-23	CHF3	11700
HFC-32	CH2F2	650
HFC-41	CH3F	150
HFC-43-10mee	C5H2F10	1300
HFC-125	C2HF5	2800
HFC-134	C2H2F4	1000
HFC-134a	CH2FCF3	1300
HFC-152a	C2H4F2	140
HFC-143	C2H3F3	300
HFC-143a	C2H3F3	3800
HFC-227ea	C3HF7	2900
HFC-236fa	C3H2F6	6300
HFC-245ca	C3H3F5	560
Sulphur hexafluoride	SF6	23900
Perfluoromethane	CF4	6500
Perfluoroethane	C2F6	9200
Perfluoropropane	C3F8	7000
Perfluorobutane	C4F10	7000
Perfluorocyclobutane	c-C4F8	8700
Perfluoropentane	C5F12	7500
Perfluorohexane	C6F14	7400

* The GWP for methane includes indirect effects of tropospheric ozone production and stratospheric water vapor production.

4.3.5.2. ReCiPe2008

The ReCiPe method assesses environmental impacts in a separate score for each impact, in midpoint approach, or with damages grouped in categories, in endpoint approach. ReCiPe was created from Eco indicator 99 (EI99) and CML2001 methods, which are commonly used to assess impacts of the life cycle for building materials and constructions [147,197,255,256]. Among the levels of uncertainties incorporation, the perspective *Hierarchist* (H) is usual in scientific works [250,251]. This study uses the midpoint approach, particularly for the impacts shown in Table 4.5.

Table 4.5 - Impacts from ReCiPe2008 analyzed

Impact	Unit
GWP100-climate change -CC	kg CO_2-Eq
Fossil depletion-FDP	kg oil-Eq
Human toxicity-HTPinf	kg 1,4-DCB-Eq
Metal depletion-MDP	kg Fe-Eq
Natural land transformation-NLTP	m^2
Ozone depletion-ODPinf	kg CFC-11-Eq
Urban land occupation-ULOP	m^2a
Water depletion-WDP	m^3

4.3.5.3. Calculation Procedures

This study used inventories data for waste treatment, transportation and packing from the EcoInvent database, version 3.2, and calculated their impacts based on the premise that:

- The life cycle impact for the treatment (sorting, recycling and landfill) is made by the multiplication of the mass of the residue and the impact per 1kg of waste,
- The impact on the transport is made by the unitary impact of the vehicle multiplied by the conveyed material mass and the distance traveled, and
- The impact on the bags treatment is made by the multiplication of the mass of bags and the impact of 1kg of bags.

Therefore, each impact factor IPCC and ReCiPe *Ip(impact)* of waste treatment and transport for each phase, is given by the Eq. 19:

$$I_p\,(impact) = Mass_p\left(\langle (SMass_s \cdot I_s) + (SMass_r \cdot I_r) + (SMass_l \cdot I_l)\rangle + \left(I_v \cdot \frac{(D_s + D_r + D_l)}{1000}\right)\right) \qquad \forall (impact) \tag{19}$$

Being the Impact of treatments in each phase *Ip(impact)* is given by the Eq. 20:

$$I_{t,p}\,(impact) = Mass_p\langle (SMass_s \cdot I_s) + (SMass_r \cdot I_r) + (SMass_l \cdot I_l)\rangle \qquad \forall (impact) \tag{20}$$

As well as, the Impact of transportation in each phase is given by the Eq. 21:

$$I_{v,p}\ (impact) = Mass_p \left(I_v \cdot \frac{(D_s + D_r + D_l)}{1000} \right) \quad \forall (impact) \tag{21}$$

In addition, the impact of packing is given by the Eq. 22:

$$I_B(impact) = \ Mass_b \cdot Mass_u / C_b \cdot I_u \quad \forall (impact) \tag{22}$$

Being, the number of bags, as in Eq. 23:

$$B = Mass_u / C_b \tag{23}$$

And the mass total of bags, as given by the Eq. 24:

$$Mass_B = \ B \cdot Mass_b \tag{24}$$

Hence, the impact of life cycle, considering waste treatment, transportation and packing of waste generated during Use and on Demolition of the building stock is given by the Eq. 25:

$$I_{lc}\ (impact) = \left(\sum_p I_p \right) + I_B \quad \forall (impact) \tag{25}$$

Where,

I_p (impact) = life cycle impact of waste during a phase p into each IPCC and ReCiPe impact (variable unit, Table 4.4 and Table 4.5).

I_{lc} (impact) = life cycle impact of waste during all phases lc into each IPCC and ReCiPe impact (variable unit, Table 4.4 and Table 4.5)

$I_{t,p}$ (impact) = life cycle impact of waste treatments during a phase p (variable unit, CO_2eq and units in Table 4.5)

$I_{v,p}$ (impact) = life cycle impact of waste transportation during a phase p (CO_2eq and units in Table 4.5)

$Mass_p$ = mass of waste in phase p (kg)

$SMass_s$ = share of waste in sorting s (%)

$SMass_r$ = share of waste in recycling r (%)

$SMass_l$ = share of waste in landfill l (%)

I_s = impact per sorting s of 1kg of waste (variable unit, CO_2eq and units in Table 4)

I_r = impact per recycling r of 1kg of waste (variable unit, CO_2eq and units in Table 4)

I_l i= impact per preparation and disposal on landfill l of 1kg of waste (variable unit, CO_2eq and units in Table 4.5)

I_v = impact per vehicle v transporting 1 ton of waste for 1km (variable unit, CO_2eq and units in Table 4.5)

D_s = distance traveled by the waste until sorting plant (km)

D_r = distance traveled by the waste until recycling plant (km)

D_l = distance traveled by the waste until landfill (km)

B = number of bags

$Mass_b$ = mass of 1 bag (kg)

$Mass_u$ = mass of waste bagged (kg)

$Mass_B$ = mass of all bags (kg)

C_b = capacity of each bag (kg)

I_b = impact for 1kg of bags (variable unit, CO_2eq and units in Table 4.5)

The mass of debris in each bag was calculated by multiplying the bag volume 20 liters (with dimensions of 48x60x10cm) by the specific weight demolition debris of 1200kg/m^3. Thus, each bag has the capacity to package 35kg of debris.

4.3.5.4. Sensitivity analysis

We compare the scenario studied with best and worst case considering the ratio of construction and demolition waste (CDW) recycling, in order to evaluate the variability of IPCC2013 and ReCiPe2008 impacts.

For the calculation of amount of waste leaving to each destination, the rates of waste recycled and reused are taken directly proportional to the ratio of variation in CDW recycling, while the rates of waste dumped in landfills have been calculated in a manner inversely proportional to the ratio of variation in CDW recycling.

4.3.6. Results and interpretation

This study evaluates the results for each impact of life cycle phases, different types of waste treatments, transportations and packing and compares impacts of GWP by IPCC2013 and ReCiPe2008 methods.

4.3.7. Limitation

Limitation of the inventory and material flow analysis for the city of Rio de Janeiro is the uncertainty generated by poor documentation and lack of standardization on statistic data. The material contained in buildings, the waste generated by them, the waste flows and area of demolitions are not known by the municipality. Especially after the implementation of the new law on waste management, the few official data on the flows of waste are not clear and remain vague. With the objective of to reduce distortions and mistakes in the elaboration of the modeled scenario, this study normalizes the statistical data and uses of empirical knowledge to fill gaps left by the vagueness of standards and statistics.

A limitation in the analysis of the life cycle impacts for construction and demolition waste in Brazilian scenarios is the difficulty of build a dataset consistent with the reality studied, due to the absence of national data in life cycle inventories. Although Brazil has been developing an initiative in LCA since 2003, the engagement of the Brazilian Institute of Information in Science and Technology (IBICT) for creation of a national database [257] is recent and still has a small amount of data from Brazilian inventories. Moreover, the methods for life cycle impacts assessment (as ReCiPe) are made from specific specifications from US, Europe and Japan [258]. This distorts the results when used in different scenarios. In order to minimize errors, this study uses midpoint impact indicators, which were neither categorized for damage types nor were normalized for cost to mitigate damage.

4.4. Results

4.4.1. Scenarios analysis

In 2010 the Brazilian solid waste policy (PNRS) [6] entered into force, and was a milestone in waste management, including construction and demolition. Since the scenarios of waste management changed in 2014 due to the implementation of the National Policy of Solid Waste [16], this study considers the previous scenario (as in 2010) between 2010 and 2013 and the new scenarios from 2014 until the end of the building stock life. Therefore, between 2010 and 2013 the construction and demolition waste were under responsibility of the city while from 2014 it was under responsibility of the waste generator and of the municipality, as suggested by the National Policy of Solid Waste.

Fig. 4.2 shows a flowchart drawn up in accordance with the interpretation of the new standard of waste management, which presents four possible cases. In the case 1 the volume of waste is reduced and the municipality is responsible for the transport and destination of the waste, preferably using recycled waste in public constructions. These case describes a scenario that tends to be waste collect from minor renovations. In the case 2, the volume of waste is relatively large, but it corresponds to still less than 10,000 m^2 of demolished area, and the construction companies are responsible for waste transportation and for hiring recycling companies. In case 3, the demolished area is greater than 10,000 m^2, but there is no space to recycle the waste in the construction site. So, the construction company must send the waste to a recycling plant, where 70% of residues must be recycled. In case 4, the area demolished is greater than 10,000 m^2 and there is space to recycle the waste in the construction site. Therefore, the construction companies are responsible for recycle and reuse at least 50% of the waste in a new construction. As the big buildings tend to be on the grounds of high commercial value, it is not advantageous to the construction company wasting time by recycling the waste on site. Since big buildings tend to be constructed in high value areas, it is not profitable to recycle waste on site. So, this case is disregarded.

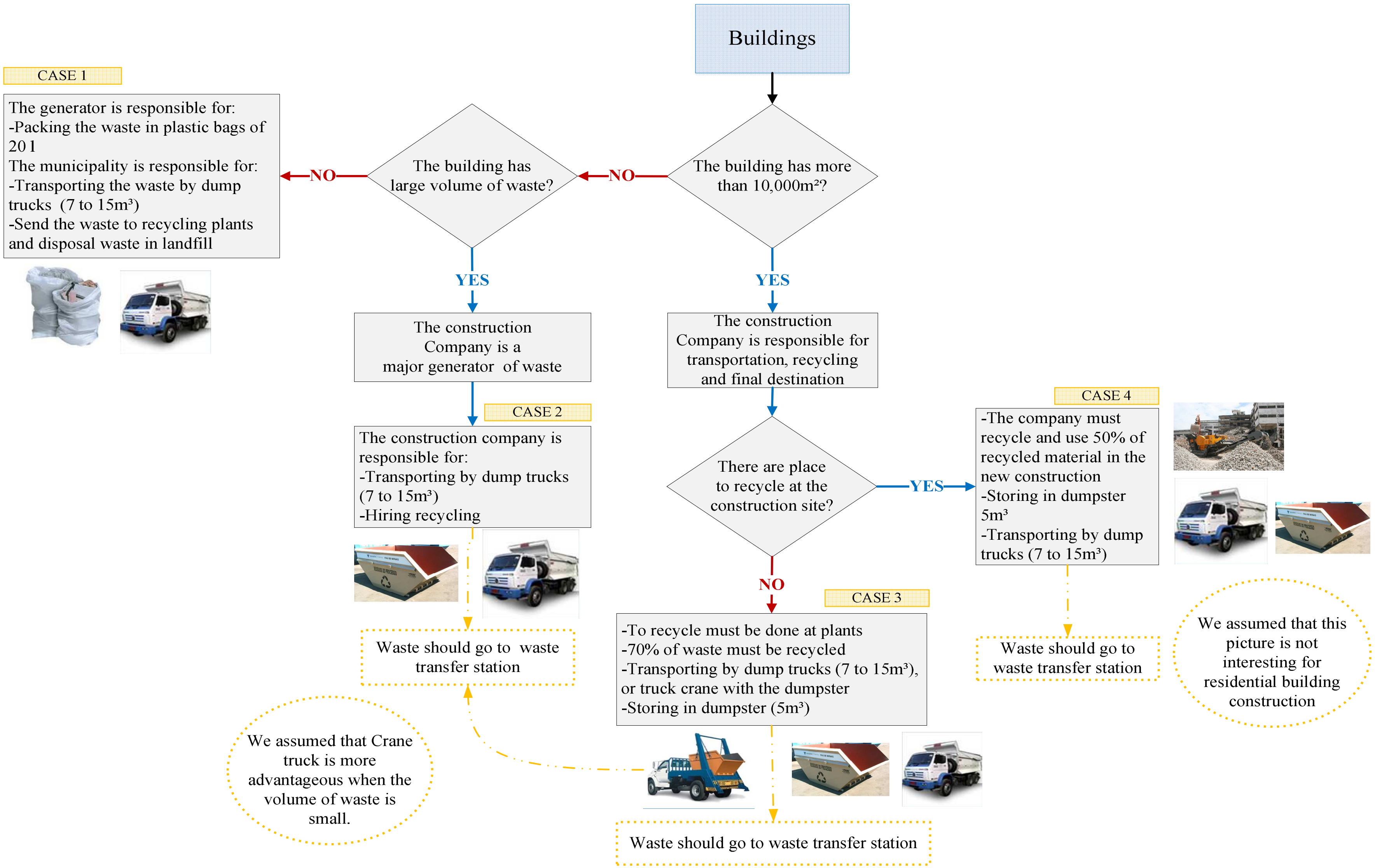

Fig. 4.2 - Flowchart of possible cases, according our interpretation of waste flows [6]

4.4.2. Characterization of waste: assumptions for modeling scenarios

4.4.2.1. Classification of construction and demolition waste

The Brazilian law of waste classification is regulated by the resolutions of CONAMA (National Environment Council) nº 307/2002 [238] and nº 431/2011 [161] and are equivalent to European standards, especially in the paragraph. 17 01 [259]. These laws classify the waste as A, B, C and D. Class A waste is reusable or recyclable as aggregates, such as residues of aggregates, concrete, cement and ceramics from structure, precast parts and against floor, brick and Grout mortar layers on the bricks in masonry, and brick masonry, ceramic bricks, concrete blocks and bricks of soil-cement. Waste of class B are recyclable for other destinations, such as: plastics, paper, cardboard, metal, glass, wood and plaster. For class C waste, there are not recycling technologies or applications economically viable yet. Waste class D are dangerous or contaminated waste that are harmful to health, such as paints, solvents, oils.

In the case of class A waste, the remnant of other materials, visually perceptible and easy sorting, are considered contaminants [260]. However, mortar has lime and cement on their composition and also, concrete takes cement. Waste of mortar and concrete are merged and are not easy to sorting. Both lime and cement can be contaminants to the environment and human health. Lima [260] analyzed samples of CDW three cities of São Paulo State, in the neighborhood of Rio de Janeiro, and he found 45% of batches analyzed for contaminants and 98% of them with undesirable materials and contaminants.

This study inventories the class A and class B waste from steel rebar, reinforced concrete, masonry, mortar and ceramic and analyze the impacts related to these materials flows. We consider the rate of 55% of waste free of contaminants and therefore recyclable.

4.4.2.2. Destination of waste

Before the PNRS, there was no standardization or specific rules and to promote the recycling of waste and most of the CDW was dumped in unsuitable location (named "*bota-fora*"), areas without any environmental protection. Before PNRS, there were some initiatives for recycling of sorted domestic waste, but the waste was not recycled; it was storage for future recycling. Those procedures were made compulsory and intensified after the PNRS and municipal plans for waste management. Between 2010 and 2013, the waste collectors companies, and construction waste generators were making adjustments to comply with the PNRS requirements.

The resolution no. 387:2005 [240] presents rules for waste management and suggests appropriate places for final destinations. According to this resolution, the class A waste should be dumped in:

- Waste processing points, including gravel quarries, that are authorized by the Municipality to recycling of debris;
- Mines authorized by the environmental agency;
- Areas for transshipment and sorting from the COMLURB (Municipal Urban cleaning Company);
- Areas for transshipment and sorting licensed by the competent environmental screening.

While the class B waste must be delivered to:

- Workers cooperative for collection and recycling of waste, authorized by COMLURB;
- Selection and recycling centers (CSRs), authorized by COMLURB;
- Recyclers companies licensed by the environmental agency;
- Areas for waste transshipment and sorting licensed by the competent environmental agency.

Even this resolution allows the concrete (class A) and the frame (class B), reinforced concrete elements, to be separated at the point of waste processing.

However, analyzing the literature we interpret that workers cooperatives, CSR, nor sorting areas of COMLURB have received construction waste. Therefore, this study disregards, from 2014 onwards, the destination for the *Missões recycling plant*, and *Caju separation plant*, so that it models the flows directly to companies licensed recyclers.

We consider separation and recycling plants as intermediary destinations for processing and preparing waste for reuse, because the material treated is re-used or disposed of in landfills elsewhere later.

The literature [238,261] states that the recycled waste materials are used as aggregates in:

- Ground leveling;
- Ecological paving;

- Manufacture of concrete for sewage infrastructure: pipes, urban facilities like benches and tables, curb, manholes covers;
- Manufacture of construction materials: brick, concrete block, concrete slabs, sand in plaster.

In recent years, some banks [20–24] have been founded as a tool of barter, purchase and sale of waste among companies and construction companies, a tool to reduce costs of waste transport, which tends to reduce environmental impacts.

One of the alternatives that have been adopted in Rio for reuse of CDW material [262–267] is the disposal of recycled waste to fill pits of quarries, as a positive and sustainable practice; since the residues are free of contaminants [268]. It has the advantage that the machinery necessary for recycling is similar to mining and locally available [269].

Between 2010 and 2013, the residues were taken to *Missões recycling plant*, to the *Caju separation plant* and *Gramacho* and *Gericinó landfills*. Later, from 2014, the waste now going to companies authorized for the separation and recycling of waste, and from there to steel recycling plants, recycled material reuse and prepared landfills.

Companies authorized by the city [270] are *Arco da aliança*, *Industria extrativa e comercial pop ltda me*, *Pedreira Copacabana ltda*, *Tamoio mineração s.a.*, *Concretran s.a.*, *Mineração Galácia ltda*, and *Solução gerenciamento de resíduos ltda*.

The *Gramacho landfill* had closed operations while *Gericinó landfill* continues to receive construction waste. In addition, *Seropédica landfill*, which was announced as a modern landfill facility for the generation of energy from the gases released by residues, went into operation in 2014. However, the amount of CDW received and the type of treatment for this type of waste was not officially released.

Table 4.6 details of destinations by type of treatment and the residue class received. The recycling and sorting plants used in the first phase did not ship treated materials, but stored for future decision. The literature does not report any decision about this material and therefore we consider the destinations between 2010 and 2013 as final destinations. The steel industry recycles the material and includes it in the manufacture of new materials. Therefore, this study considers the steel industry as a final destination for the scraps. Therefore, this study considered the *Thyssenkrupp CSA Siderúrgica do Atlântico* as the target of reference to analyze flows.

Table 4.6 – Details of treatments type, destiny type and type of waste receipt by the destinations of CDW

Destiny	Treatment	Type	Waste class A	Waste class B	Waste class C
Missões	Recycling	Final	X	N/A	N/A
Caju	Sorting	Final	X	N/A	N/A
Gramacho	Landfill	Final	X	N/A	N/A
Gericinó	Landfill	Final	X	N/A	N/A
Seropédica	Landfill	Final		N/A	N/A
(I) Arco da aliança	Sorting and recycling	Intermediary	X		
(II) Industria extrativa e comercial pop ltda me	Sorting and recycling	Intermediary	X	X	
(III) Pedreira copacabana ltda	Sorting and recycling	Intermediary	X	X	X
(IV) Tamoio mineração s.a.	Sorting and recycling	Intermediary	X	X	X
(V) Concretran s.a.	Sorting and recycling	Intermediary	X		
(VI) Mineração galácia ltda	Sorting and recycling	Intermediary	X		
(VII) Solução gerenciamento de resíduos ltda. Me	Sorting and recycling	Intermediary	X	X	X
Thyssenkrupp CSA Siderúrgica do Atlântico	Recycling (steel plant)	Final		Steel	

4.4.2.3. *Processes: treatments and reuse*

The waste, treatments and streams were characterized based on academic literature, technical reports and interpretation of standards.

4.4.2.3.1. *Demolition*

The demolition methods are: manual, mechanical (by wrecking balls, knobs, cables or planned collapse when a machine pushes the construction until it breaks apart), and explosives [271].

4.4.2.3.2. *Sorting*

The sorting of CDW is made in manual or mechanical way. In manual sorting, the waste is disposed on the ground by tractor and the impurities are separated by hand. In mechanical sorting, the waste is thrown on a treadmill, selected by hand and separated into boxes [264,272,273].

4.4.2.3.3. Recycling

The class A waste are sorted first from wood, organics and other types of waste and after from metals (class B). For the class A recycling, the waste is crushed for reduction of the volume and processing, and sorted for particle size separation [264,272,273]. The outcomes are sand and gravel in different particle sizes. For the steel recycling, the scrap is pressed, transported to the plant, where they are melted down and are inserted into the production of new materials, as described in the flow chart in Fig. 4.3.

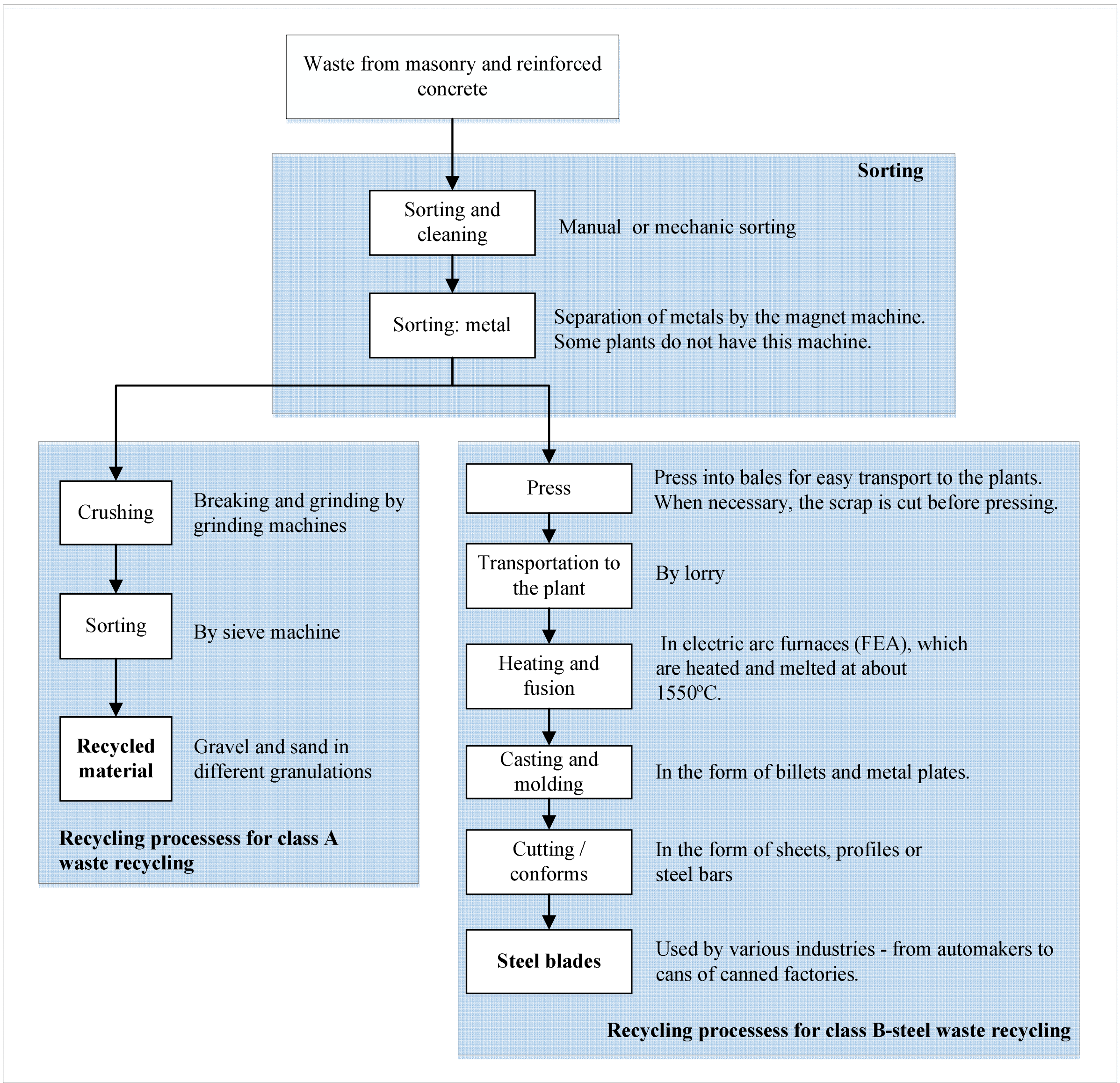

Fig. 4.3 – Processes for waste sorting, for class A waste recycling [260,261] and for class B steel waste recycling [274].

4.4.2.3.4. Landfill

The construction waste dumped in inert landfills is previously sorted at the construction site or in temporary destinations. The waste is dumped in overlapping layers and segregated to allow future reuse or recycle material [275].

4.4.2.3.5. Transportation

The transportation is made by dump trucks of 7 to 15m³ or truck crane [217] on roads network, which are underperform as compared to international standards [27].

4.4.2.3.6. Package

The waste standards suggest that small volumes must be packed in 20l bags, to be collected by the municipality [194]. The amount of plastic on the bags was calculated by the equations 9, 10 and 11. Table 4.7 shows the results of bagged and plastic waste from the bags.

Table 4.7 – Mass of bagged waste, number of bags and mass of plastic from the bags

	Mass of bagged waste (kg)	% of waste	Number of bags	Mass of plastic (kg)
AP1	453,524,544.17	5%	12,957,844	194,368
AP2	2,840,578,695.22	30%	81,159,391	1,217,391
AP3	3,462,922,068.36	36%	98,940,631	1,484,109
AP4	1,573,117,551.51	16%	44,946,216	674,193
AP5	1,279,431,046.63	13%	36,555,173	548,328
RJ	9,609,573,905.87	100%	274,559,254	4,118,389

4.4.2.3.7. Reuse

Regardless of what kind of reuse recycled waste has (if landfill, infrastructure or construction), the distance is normalized in 20km for the calculation of distance and transportation impact.

4.4.2.4. Modeling flows

We created a scheme with possible scenarios to define as a coherent intermediate scenario. This scheme is based on PNRS constraints (50% of waste recycled in the construction site and 70% recycled plant) and contamination rates of 55% described by Lima in his inventory[260] for the city of Macaé, in Rio de Janeiro State. The worst case has a rate of contamination 25% higher while the best case has a rate of contamination 25% lower than the intermediate one. We assume that waste free of contamination is recycled.

- Case 1: considers that the intermediary case has 55% residue free from contamination, a worst case has 44% waste free of contamination and the best case has 76% waste free of contamination.
- Cases 2 and 3: the worst case is limited by the standard (PNRS) of 70% of recycled waste, the best case has 76% waste free of contamination, and the intermediate case has 73% (average) waste free of contamination.
- Case 4: the worst case is limited by the standard 50% of recycled waste, the best case has 75%, and the intermediate case (average) has 62% waste free of contamination.

Case 1 encompasses the collection of small amounts of waste that are responsibility of the City Council, which tends to be small. Therefore, this study applies this case during the Use phase.

Cases 2 and 3 addresses large volume of waste generation. In both cases, the construction companies have the responsibility for shipping and recycling. They are similar in amount of recyclable waste and this study uses them for the demolition of buildings.

Demolition waste of single-family houses also were framed in cases 2 and 3, because, in Rio de Janeiro, there is a tendency to be from single-family homes for the construction of multi-family buildings, which is often performed by construction companies. In addition, usually, more than one house at a time is demolished, and the amount of waste generated is large.

As described in the scenario analysis, we discard case 4. We use the intermediate scenario for the LCIA.

The amount of waste for each target has been set for 2010, by statistical data of waste collection [215,217,276], and for 2014 onwards, these situations are bounded by the standards of waste and contamination rates already described.

4.4.2.4.1. Waste flows

Fig. 4.4 shows the intermediate scenario in flowcharts: the waste streams modeled for the first phase of the use of buildings, from 2010, that is, between the years 2010 and 2013; and the waste streams modeled for the second phase of use and demolition of buildings, between the years 2014 and the demolition of buildings.

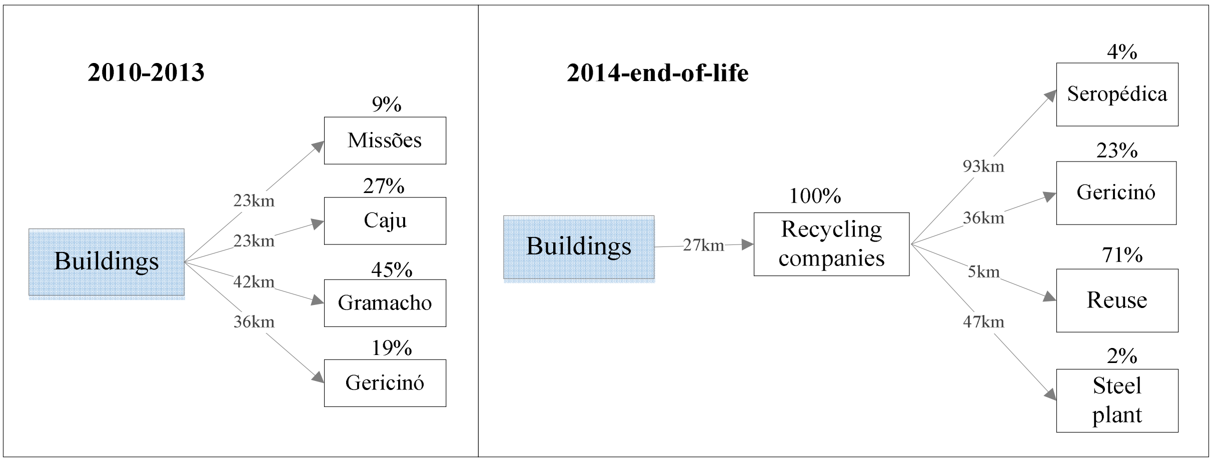

Fig. 4.4 – Waste flows as 2010 (between 2010 and 2013) and flows as 2014 (from 2014 until the demolition of the buildings)

4.4.3. Inventory by Material Flow Analysis

4.4.3.1. Amount of waste and annual ratio of waste generation

The amount of material was calculated in the previous chapter, by the extrapolation of material intensity for 4 buildings model. The mass of waste from concrete, steel, cement, aggregates and ceramic generated by the 2010 stock between 2010 and 2013, 2014 and its end of life and on its demolition, at different moments in the city of Rio de Janeiro, were calculated in the Chapter 3. The general data is presented in the Table 4.8 while the details are presented in the Supplementary data.

Table 4.8 - Waste generated by the building stock 2010 during its phases

Original material	2010-2013 (t)	2014-End of life (t)	Demolition (t)	2010-Demolition
Concrete	953	309,712	51,748,921	52,059,586
Steel	67	19,557	2,336,989	2,356,614
Cement	1753	501,846	3,235,132	3,738,732
Aggregates	30,959	8,628,229	13,236,137	21,895,326
Ceramic	418	116,076	1,884,120	2,000,615

Fig. 4.5 illustrates the total quantity of waste from the materials of greater intensity in residential buildings by sub region.

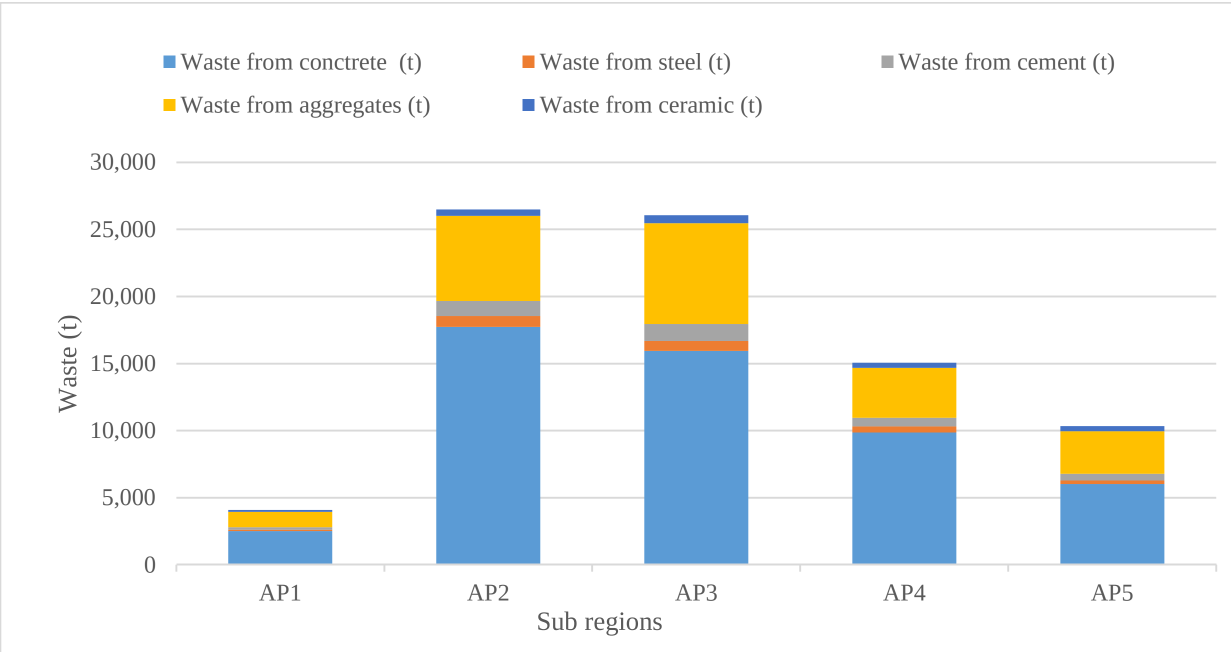

Fig.4.5 - Waste from the main materials per sub regions

The potential annual rates of waste generation by buildings types, which were found in Chapter 3, are 0.2% to 0.4% for SFH, MFB-4F, 0.3% to MFB-8F and 0.1% to MFB-16F. They serve as the basis for calculating waste generation between 2010 and 2013.

4.4.3.2. Distances traveled

4.4.3.2.1. Reference coordinates

This study defined reference points for sub-regions as sources for calculating the distance traveled in the waste transport. The location reference points by Latitude and Longitude coordinates for the source and destination of the waste is shown in supplementary data.

The occupation ratios from sub region, expressed by the Total Constructed Area (TCA), were used to calculate the weighted average distances of waste transport. They are described in Table 4.9.

Table 4.9 - Area and ratio of occupation of sub regions and city from TCA

Ratio of Occupation		
Sub region / city	Total and per sub region TCA (m²)	Rate of TCA
AP1	4,899,889	5%
AP2	37,300,014	35%
AP3	33,588,559	31%
AP4	19,976,568	19%
AP5	11,947,923	11%
RJ	107,712,953	100%

4.4.3.2.2. Measuring distances

The distance to the waste transport in the second phase of use was calculated in two steps:

1. From the origin of demolition for intermediate targets, whereas the weighted average of the distances between the points of references of the sub-regions and the companies authorized for separation and recycling of waste (shown in supplementary data.);
2. Regarding the intermediate destinations for final destinations calculated by weighted averages of distances, whereas each company receives the same amount of waste and the

final destinations receive the rates adopted in drawing up the scenario studied (shown in supplementary data.). The measurements were taken using Google maps [207].

4.4.4. LCIA: Dataset and unitary impacts

Table 4.10 shows the Center EcoInvent dataset used for the calculations of lifecycle impacts, whereas the processes of treatments, separation, recycling, transport and packaging. The demolition process itself was not found in the database, so it was not considered.

Table 4.10 - Dataset from EcoInvent adopted for LCIA

Dataset EcoInvent 3.2	
Waste from materials	Activities Name, Geography
Concrete, cement, aggregates	*"Treatment of waste concrete, inert material landfill, RoW"*
Concrete, cement, aggregates	*"Treatment of waste reinforced concrete, recycling, RoW"*
Concrete, cement, aggregates	*"Treatment of waste reinforced concrete, sorting plant, CH"*
Brick, ceramic tile	*"Treatment of waste brick, collection for final disposal, CH"*
Brick, ceramic tile	*"Treatment of waste brick, recycling, CH"*
Brick, ceramic tile	*"Treatment of waste brick, sorting plant, CH"*
Reinforced steel	*"Treatment of waste reinforcement steel, collection for final disposal, CH"*
Reinforced steel	*"Treatment of waste reinforcement steel, recycling, CH"*
Reinforced steel	*"Treatment of waste reinforcement steel, sorting plant, CH"*
Transport	Activities Name, Geography
Dump trucks (7 to 15m³), or truck crane with the dumpster	"Transport, freight, lorry 7.5-16 metric ton, EURO3, GLO"
Package	Activities Name, Geography
Plastic bag, 20l	"Treatment of waste polypropylene, sanitary landfill, RoW"

Table 4.11 - Impacts for each process, considering 1 kg of waste

Impact	Unit	Sorting (1kg)	Recycling (1kg)	Steel recycling (1kg)	Landfill (1kg)	Transport (t·km)	Package (kg)
GWP100a	CO_2eq	7.23E-02	8.46E-03	5.73E-02	1.34E-01	2.15E-01	4.36E-02
CC	kg CO_2-Eq	7.31E-02	8.62E-03	5.79E-02	1.38E-01	2.18E-01	9.53E-02
FDP	kg oil-Eq	2.70E-02	5.00E-03	2.11E-02	5.29E-02	8.13E-02	6.34E-03
HTPinf	kg 1,4-DCB-Eq	3.93E-02	1.05E-03	3.54E-03	1.86E+00	4.95E-02	3.51E-01
MDP	kg Fe-Eq	3.47E-03	3.48E-04	2.15E-03	1.98E-02	9.04E-03	7.72E-04
NLTP	m_2	2.12E-05	-3.87E-05	2.18E-05	-4.54E-05	8.28E-05	-4.32E-05
ODPinf	kg CFC-11-Eq	1.41E-08	2.40E-09	1.06E-08	6.36E-08	3.93E-08	2.74E-09
ULOP	m_2a	1.20E-03	1.03E-03	1.30E-04	6.55E-03	9.48E-03	3.80E-03
WDP	m_3	6.95E-05	1.20E-05	2.85E-05	1.10E-03	2.19E-04	3.48E-05

The results of the assessment of impacts of waste generated by the stock of buildings for their use from 2010 and its demolition, detailing each step, depending on the destinations (as sub flows) are shown in Table 4.12 and the participation of each impact is shown in Fig. 4.6.

Considering the functional unit of the building stock, the landfill of *Gericinó* (30% in GWP, CC, FDP; 80% 55% HT; MDP; -45% and 45% in NLTP; in ODP and ULOP) and repair companies and class A waste recycling are the most influential in generating impacts (65% in GWP, CC and FDP; 38% 55% in MDP; 5% in ODP; HTP; and-50% in NLTP). Despite the small amount of recycled steel, compared to concrete and other class A waste, recycling of shows enough pollutant (20% in HT; 10% MDP and ODP; and between 5% and 9% for the other impacts). Thus, the impacts of HTP and WDP dominate among the system impacts and natural land transformation potential, as expected, is expressive in inert landfill targets and recycling.

The results of the assessment of impacts of waste generated by the stock of buildings categorized under treatment, transport and packaging are presented in Table 4.13 and the participation of each impact in percentage are shown in Fig. 4.7.

Regarding these categories of analysis, the impact of transport to reach 10%, the impacts of packaging are negligible while the impacts of the treatments (separation, recycling and landfill) are more representative. HTP and impacts of WDP give themselves almost entirely because of the treatments. Transportation had a NLTP impact of 10%, while waste treatment had a NLTP impact of -90%. The negative value represents benefit. The impacts of transportation were a concern because vehicles usually cause major GHG emissions at fossil fuel burning and contribute to GWP, CC and FDP. However, the impacts from waste transportation are small in comparison with the impacts from recycling processes.

The results of the impacts assessment of waste generated by the stock of buildings considering the use and demolition phases are presented in Table 4.14 and the percentage of each impact is illustrated in Fig. 4.7. Considering the different phases, no impact stood out. As expected, the demolition phase is responsible for the majority of impacts (50%).

Table 4.12 – Life cycle Impacts IPCC2013 and ReCiPe2008 for the stock of buildings from 2010 to their end of life, considering the waste destinations.

	2010-2013			2010-End of life	2014-End of life and demolition				
Impact	Caju (Sorting)	Missões (Recycling)	Gramacho (Landfill)	Gericinó (Landfill)	Seropédica (Landfill)	Companies (Sorting and recycling)	Steel Plant (Steel Recycling)	Variable (Reuse)	Total
GWP	7.12.E+05	4.12.E+04	2.20.E+06	2.62.E+09	4.55.E+08	5.38.E+09	1.11.E+08	6.26.E+07	8.63.E+09
CC	7.20.E+05	4.19.E+04	2.26.E+06	2.70.E+09	4.69.E+08	5.44.E+09	1.12.E+08	6.36.E+07	8.79.E+09
FDP	2.66.E+05	2.11.E+04	8.66.E+05	1.03.E+09	1.80.E+08	2.12.E+09	4.09.E+07	2.37.E+07	3.40.E+09
HT	3.73.E+05	6.72.E+03	2.86.E+07	3.52.E+10	6.11.E+09	2.54.E+09	9.62.E+06	1.44.E+07	4.39.E+10
MDP	3.39.E+04	1.71.E+03	3.09.E+05	3.77.E+08	6.55.E+07	2.51.E+08	4.23.E+06	2.63.E+06	7.01.E+08
NLTP	2.13.E+02	-1.13.E+02	-6.44.E+02	-8.20.E+05	-1.43.E+05	-8.42.E+05	4.22.E+04	2.41.E+04	-1.74.E+06
ODPinf	1.38.E-01	1.01.E-02	1.00.E+00	1.22.E+03	2.12.E+02	1.08.E+03	2.04.E+01	1.14.E+01	2.55.E+03
ULOP	1.31.E+04	3.84.E+03	1.07.E+05	1.28.E+08	2.22.E+07	1.58.E+08	9.43.E+05	2.76.E+06	3.11.E+08
WDP	6.87.E+02	5.23.E+01	1.71.E+04	2.09.E+07	3.63.E+06	5.43.E+06	6.35.E+04	6.37.E+04	3.01.E+07

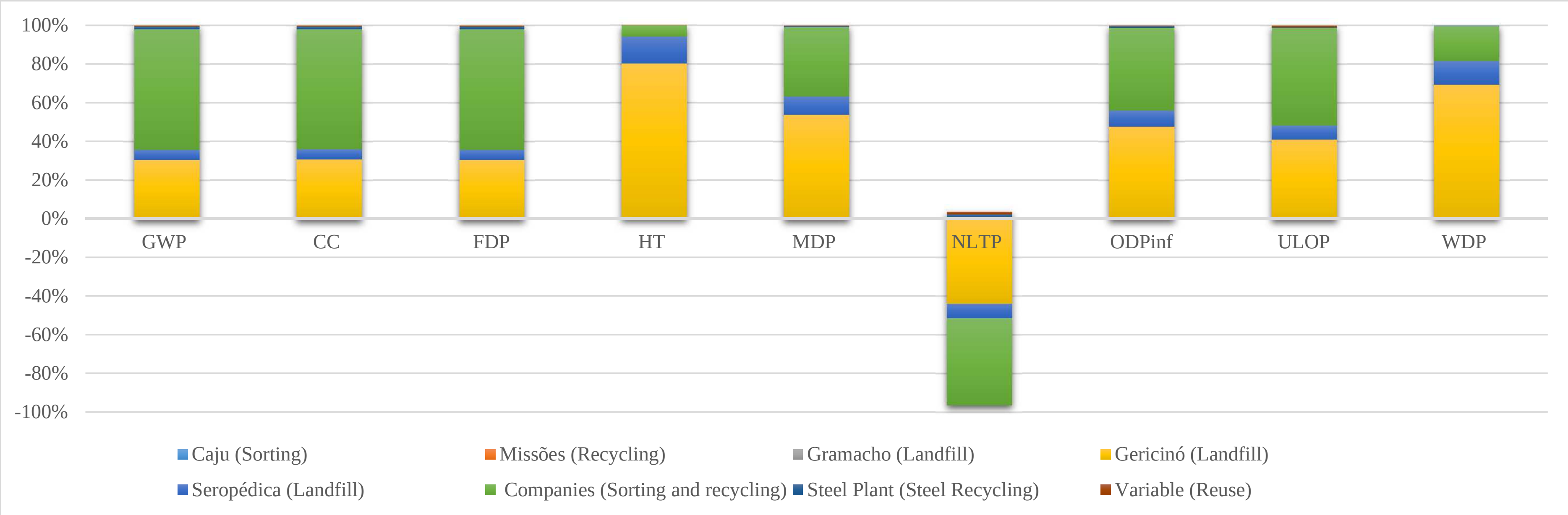

Fig. 4.6 - Participation of the life cycle impact of waste generated by the building stock considering the different destinations.

Table 4.13 - Life cycle Impacts IPCC2013 and ReCiPe2008 for the stock of buildings, in function of the destinations.

	GWP	CC	FDP	HT	MDP	NLTP	ODPinf	ULOP	WDP
Treatment	8.E+09	8.E+09	3.E+09	4.E+10	7.E+08	-2.E+06	2.E+03	3.E+08	3.E+07
Transportation	6.E+08	7.E+08	2.E+08	1.E+08	3.E+07	2.E+05	1.E+02	3.E+07	7.E+05
Package	2.E+05	4.E+05	3.E+04	1.E+06	3.E+03	-2.E+02	1.E-02	2.E+04	1.E+02

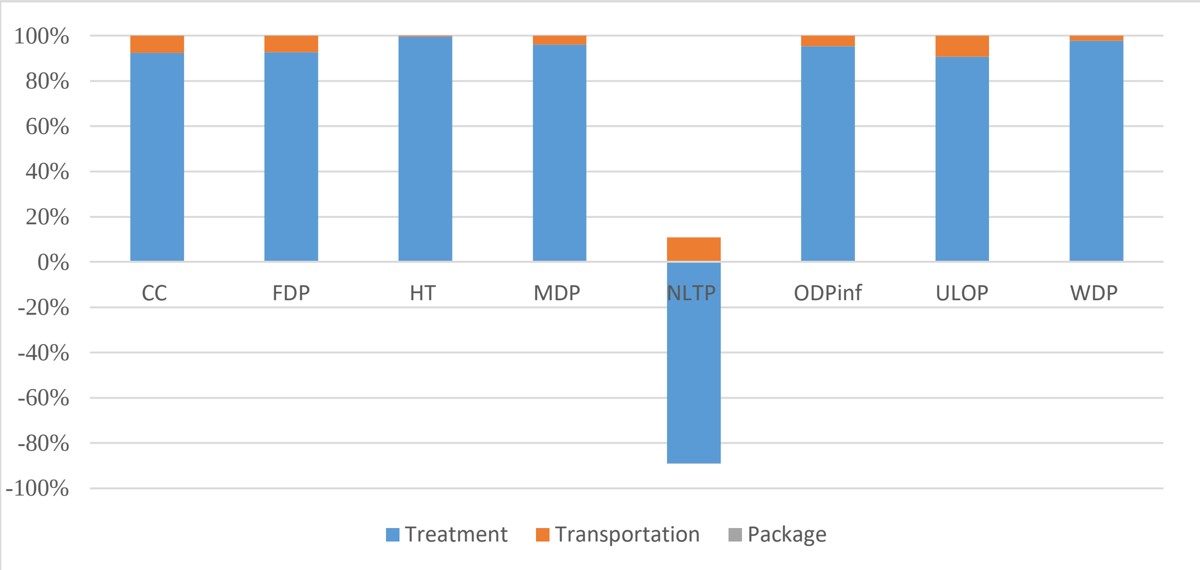

Fig. 4. 7 - Participation of the life cycle impact of waste generated by the building stock considering treatments, transportation and package.

Table 4.14 – Life cycle Impacts IPCC2013 and ReCiPe2008 for the stock of buildings, in function of the phases of use and demolition.

Impact	GWP	CC	FDP	HT	MDP	NLTP	ODPinf	ULOP	WDP
Use	1.E+09	1.E+09	4.E+08	5.E+09	8.E+07	-2.E+05	3.E+02	4.E+07	4.E+06
Demolition	8.E+09	8.E+09	3.E+09	4.E+10	6.E+08	-2.E+06	2.E+03	3.E+08	3.E+07

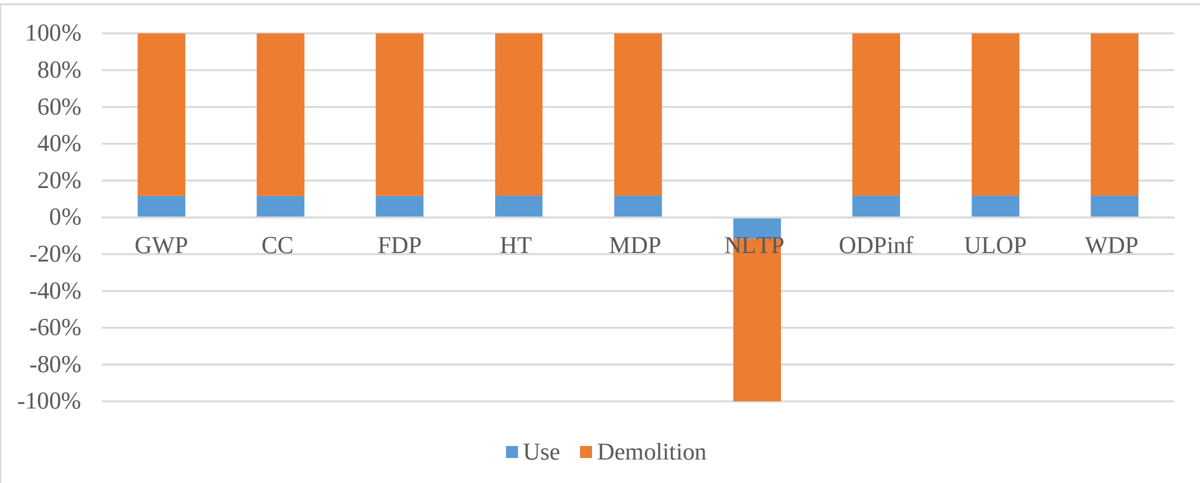

Fig. 4.8 – Participation of the life cycle impact of waste generated by the building stock considering use and demolition phases.

The results of the assessment of the ReCiPe impact categories resulting from the waste generated by the building stock for their use from 2010 until its demolition in function of the destinations are presented in Table 4.15. Fig. 4.9 illustrates the percentage of each waste destination, considering each ReCiPe impact. The *Caju sorting plant* is the only destination that has negative NLTP (-40%), that is, which brings more benefits than losses for the environment [277,278]. This plant is distinguished by high CC impacts and FDP (42%). The *Gericinó landfill* was the biggest impact proportional to its other impacts (80% in 50% ULOP; WDP; 60% to 70% in ODP; 60% NLDP; MDP; and 85% in HTP), except for the CC and FDP (40%), which is highest in the separation and recycling companies. The companies also have high impacts on ULOP and NLTP. The *Missões recycling plant* has slightly stronger NLTP impact than other impacts. Reuse seems practically nonexistent, which is predictable, since only the transport accounts for the impacts of this final destination. The impacts of *Seropédica landfill* are low and stable, because the amount of construction waste dumped there is small.

Table 4.15 – ReCiPe2008 life cycle impacts of waste considering destinations, from 2010 until the end of the life of the stock.

	CC	FDP	HTPinf	MDP	NLTP	ODPinf	ULOP	WDP
Companies, sorting and recycling	8E+05	3E+05	4E+05	4E+04	-1E+02	2E-01	2E+04	8E+02
Steel Plant, recycling	2E+04	6E+03	1E+03	6E+02	6E+00	3E-03	1E+02	9E+00
Seropédica, landfill	7E+04	3E+04	9E+05	9E+03	-2E+01	3E-02	3E+03	5E+02
Gericinó, landfill	7E+05	3E+05	9E+06	1E+05	-2E+02	3E-01	3E+04	5E+03
Variable, reuse	9E+03	3E+03	2E+03	4E+02	3E+00	2E-03	4E+02	9E+00
Caju, sorting plant	2E+05	9E+04	1E+05	1E+04	7E+01	5E-02	4E+03	2E+02
Missões, recycling plant	1E+04	7E+03	2E+03	6E+02	-4E+01	3E-03	1E+03	2E+01
Total	2E+06	7E+05	1E+07	2E+05	-3E+02	5E-01	6E+04	7E+03

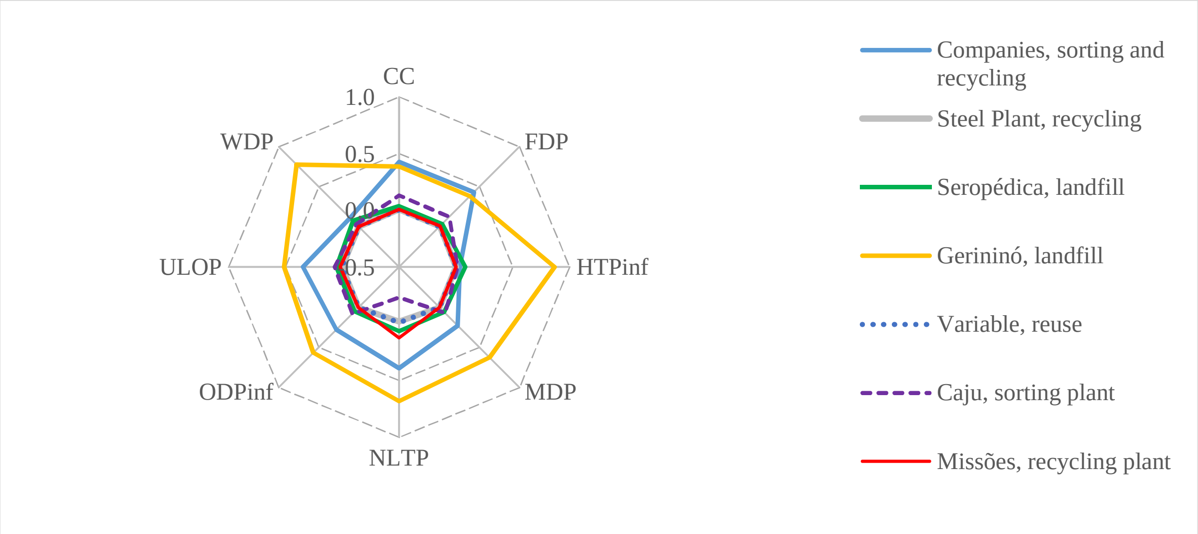

Fig. 4. 9 - Categorized impacts ratios from ReCiPe2008 for the *waste destinations* from 2010 to the end of life.

The ReCiPe impacts of waste flows, as they were in 2014, for 1kg of waste, are shown in Table 4.16. Fig. 4.10 illustrates the proportion of each stream at each impact. Considering only 1 kg of waste in each stream, the flow into the steel recycling is dominant in all impacts (between 40% and 50% of every kind of impact), with the exception of the HTP (below 30%); in addition, the results for this flow does not demonstrate great benefit in iron ore consumption function of MDP (around 45% of this impact). The impacts of the recycling of other materials are considerably reduced in relation to the impacts of steel recycling, being negative in all types of impacts and, consequently, being beneficial to the environment [277,278]. The impacts of streams to landfills are average for all impacts (20% to 30%), except for HTP (around 35% of this impact).

Table 4.16 - Categories of ReCiPe2008 life cycle impacts to waste streams from stock of buildings between intermediate and final destinations, considering 1 kg of waste.

	CC	FDP	HTPinf	MDP	NLTP	ODPinf	ULOP	WDP
Buildings-companies-steel plant	1E+01	4E+00	2E+00	4E-01	4E-03	2E-06	4E-01	1E-02
Buildings-companies-reuse	1E+00	4E-01	3E-01	5E-02	4E-04	2E-07	5E-02	1E-03
Buildings-companies-Gericinó	5E+00	2E+00	3E+00	2E-01	2E-03	1E-06	2E-01	6E-03
Buildings-companies-Seropédica	5E+00	2E+00	3E+00	2E-01	2E-03	1E-06	2E-01	6E-03

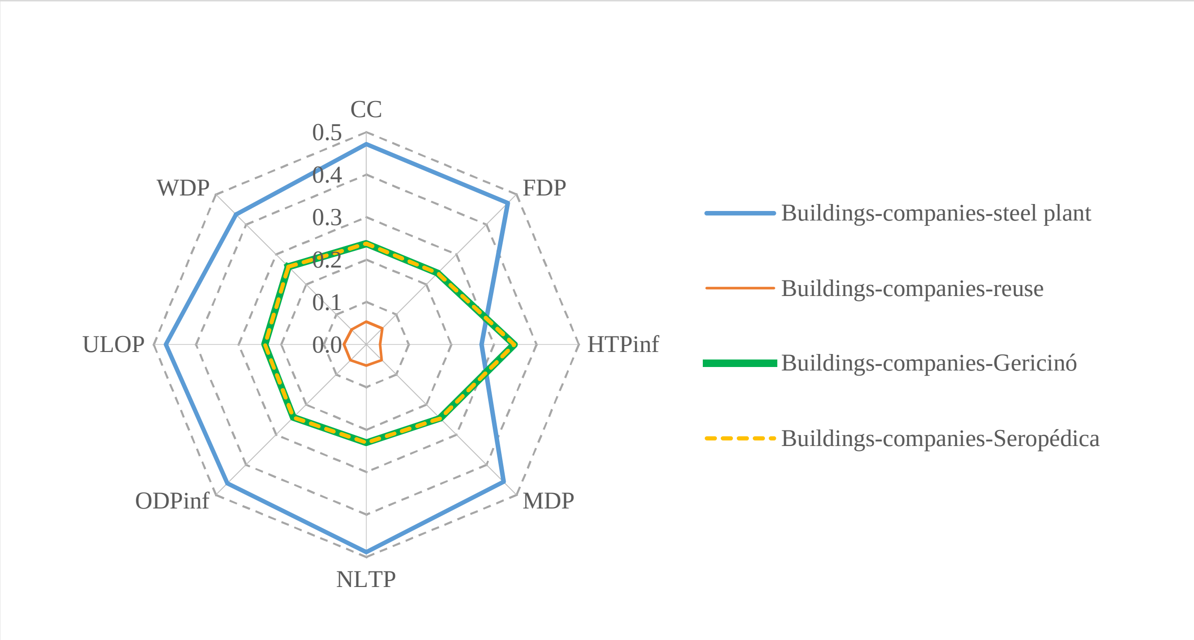

Fig. 4.10 - Categorized impacts ratios from ReCiPe2008 for *flows as 2014*, considering 1kg of waste.

4.4.5. Sensitivity analysis

The rate of 50%-70% for recycling waste class required by the PNRS is quite ambitious, primarily to consider the situation before PNRS uncontrolled dump in inappropriate places. Therefore, the sensitivity analysis evaluates changes in the overall impacts (Table 4.17), increasing and decreasing by 10% of recycled waste. The percentage of recycled waste reached 73%, the pessimistic scenario was 63% and the optimistic was 83% of waste recycled. A sensitivity analysis covers the total scenario: intermediary and final destination, considering all the waste generated from the building stock from 2010.

Table 4.17 – Receiving waste percentage by destination.

Scenarios	Recycling	Seropédica	Gericinó	Steel Plant	Reuse
Optimistic	83%	4%	20%	3%	81%
Medium	73%	4%	23%	2%	71%
Pessimistic	63%	4%	27%	3%	61%

The results of the sensitivity analysis are shown in percentages in Fig. 4.11. Based on the scenario studied, the optimistic scenario has increased primarily impacts GWP (9%), CC (8%), FDP (9%), followed by NLTP (7%), ODP (6%), PRM (5%), WDP (2%) and HTP (1%). The pessimistic scenario has increased primarily impacts HTP (13%) (10%), and WDP followed by MDP (5%), ODP (3%) and (1%), NLTP kept unchanged ULOP and decreased impacts GWP (3%), CC (3%) and the FDP (3%).

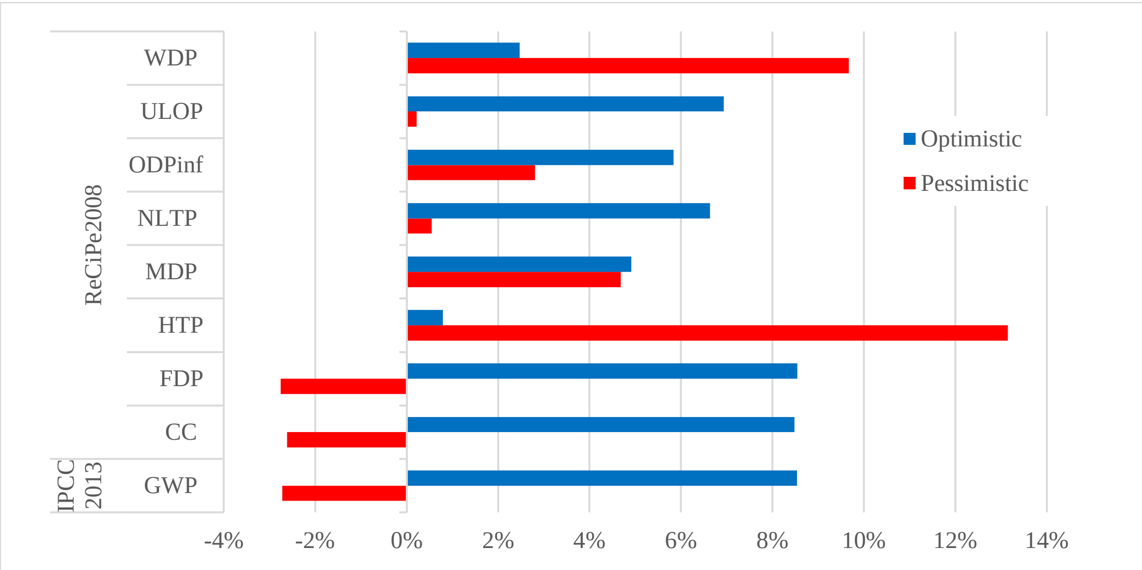

Fig. 4.11 - Results of variations impacts the pessimistic and optimistic scenarios

4.5. Interpretation, discussion and recommendations

Results of the percentage of each waste disposal for each impact shown in Fig. 4.9 suggest that the *Gericinó Landfill* is dominant in WDP and HTP and pollutants in all other impacts.

The comparison of impacts ratios from ReCiPe2008 for categorized into *flows as 2014 (*considering 1kg of waste) is shown in Table 4.16 and Fig. 4.10 demonstrated that, comparing all flows, the flow buildings-companies-steel plant is more pollutant in all impacts except in HTP while recycling of other materials.

In the sensitivity analysis, considering a comparison between the results of variations in impacts by the pessimistic and optimistic scenarios shown in Fig. 4.11, the increase in the recycling rate represents an increase of GWP, CC and FDP impacts and decreased impacts HTP and WDP.

The use of construction waste for revitalization of disabled mines if not done properly can contaminate the environment if not done properly.

In relation to the LCIA, a solution to minimize errors by regional differences (technology) can be the regionalization of the dataset [279], which is unfeasible without inventories in Brazil.

Given the results found and discussed, we suggest further measures to prevent and manage waste in Rio de Janeiro:

- Control of recycling processes of class A waste and mainly of steel (class B) in terms of GHG emissions;
- Carrying out inventories and cataloguing of material inputs and outputs in the processes and flows separating and recycling companies within the community;
- Carrying out inventories and cataloguing of cost and price of recycling, as well as work time of employees;
- Conducting inventories and cataloguing of transport of waste and recycled material, whereas the fleet used on the type of vehicle, capacity, age, production cost and maintenance, fuel type used, and routes travelled;
- Technological research incentives for recycling of building materials is viable to the reality of Brazil;

- Constant supervision in the use of recycled material when filling inactive mines to avoid environmental impact caused by contaminants that may disrupt the process of revitalization of the mines;
- Elaboration of educational brochures aiming to instruct stakeholders for prevention waste;
- Encouraging projects as modular dimensions standards, to facilitate maintenance and demolition;
- Encouraging the elaboration of projects for demolition every construction;
- Do marketing campaigns to convince people that waste is potential material;

The standard of waste (PNRS) is quite ambitious and that is met, the tax incentive and control if necessary. The standard of buildings performance (NBR 15575) is important to ensure proper operation and to extend the lifetime of buildings, but we recommend actions for the prevention (or reduction) of waste generation;

We believe that impacts from waste can significantly decrease if the architectural and engineering designs have in mind an efficient use of materials and waste prevention; as well as , incentives for preparation of management and waste recycling plans for any construction, expansion or renovation can change the habit of Brazilians to dump waste at unprepared sites.

Results show that waste recycling represents many impacts, but the dematerialization of the construction sector and the preservation of natural resources depletion depends heavily on it. Hence it is important to mitigate the impacts and to use the material efficiently.

4.6 Conclusion

In this chapter, we used Life Cycle Assessment combined with Material Flow Analysis in order to assess environmental impacts of the waste flows of the building stock of the city of Rio de Janeiro, from 2010 to the end of their life. We used the results of the materials and waste flows from the building stock described in the chapter 3 to assess life cycle impact of these waste flows. First, we set a scenario of waste flows according to policies, standards and waste contamination rates. Next, we assessed the scenarios on life cycle impacts generated, focusing on the comparison of impacts from flows, treatments, and package; use and demolition phases; sub flows. We considered the partial flows per destination type; and complete flows, that cover origin, intermediary destination and final destination. Then, we compared the impacts of the waste flows of the buildings from 2010 to the end of their life with the impacts of optimistic and pessimist scenarios by sensitivity analysis, highlighting the variations in each impact. Finally, we discussed and interpreted the results.

This evaluation demonstrates, by a quantification of the impacts, that the attitude of the Brazilian Government to encourage the recycling of waste, especially the class A and prevent the dumping of construction waste at landfills is obviously adequate. However, we suggest that the municipality controls the waste treatments and elaborates of surveys of the current scenario. We also recommend actions to promote the prevention of waste generation and increase of consumer acceptance of using recycled residue. This study should help decision-makers in setting goals for management and recycling of construction and demolition waste. The analysis of the results provides a deeper insight of impact loads from waste flows and underlies conscious decisions to development goals to reduce their environmental impact.

4.7 Nomenclature

4.7.1 Abbreviations

PNRS	*National Solid Waste Policy*
LCIA	*Life cycle impact assessment*
LCA	*Life cycle assessment*
MFA	*Material Flow Analysis*
GHG	*Greenhouse gases*
CDW	*Construction and demolition waste*
SMAC	*Municipal Secretariat of the Environment*
COMLURB	*Municipal Company of Urban Cleaning*
TCA	*Total constructed area*
CSR	*Recyclables Separation Center*
IBICT	*Brazilian Institute for Information in Science and Technology*

4.7.1.1 Acronyms of the impacts

GWP	*Global warming potential*
CC	*Climate change*
FDP	*Fossil depletion potential*
HTP	*Human toxicity potential*
NLTP	*Natural land transformation potential*

ODP	*Ozone depletion potential*
ULOP	*Urban land occupation potential*
WDP	*Water depletion*

4.7.2. Equations

4.7.2.1 Inventory

PWb	*Potential of waste generation for building type*
LOb,s	*Shared of land occupation of the buildings type per sub region*
Wc,q	*Waste generated between 2010 and 2013, considering the buildings in the city*
Ws,q	*Waste generated between 2010 and 2013, considering the buildings in the sub regions*
y	*Number of years of buildings use*
PWb,q	*Potential of waste generation for building type between 2010 and 2013*
PWb,y	*Annual potential of waste generation for building type*
Wc,n	*Waste generated from 2014 to the end of the buildings life, considering the buildings in the city*
Ws,n	*Waste generated from 2014 to the end of the buildings life, considering the buildings in the sub regions.*

4.7.2.1.1 Indices

b	*Building type*
s	*Sub region*
c	*City*
y	*Number of years*
q	*During use phase, between 2010 and 2013*
n	*During use phase, from 2014 to the end of the buildings life*

4.7.2.2 LCIA

I_p *(impact)*	*Life cycle impact of waste during a phase p into each IPCC and ReCiPe impacts*
I_{lc} *(impact)*	*Life cycle impact of waste during all phases lc into each IPCC and ReCiPe impacts*
$I_{t,p}$ *(impact)*	*Life cycle impacts of waste treatments t during a phase p*
$I_{v,p}$ *(impact)*	*Life cycle impacts of waste transportation v during a phase p*
$Mass_p$	*Mass of waste in phase p*
$SMass_s$	*Share of waste in sorting s*

$SMass_r$	*Share of waste in recycling r*
$SMass_l$	*Share of waste in landfill*
I_s	*Impact per sorting s of 1kg of waste*
I_r	*Impact per recycling r of 1kg of waste*
I_l	*Impact per preparation and disposal on landfill l of 1kg of waste*
I_v	*Impact per vehicle v transporting 1ton of waste for 1km*
D_s	*Distance traveled by the waste until sorting plant*
D_r	*Distance traveled by the waste until recycling plant*
D_l	*Distance traveled by the waste until landfill*
B	*Number of bags*
$Mass_b$	*Mass of 1 bag*
$Mass_u$	*Mass of waste bagged*
$Mass_B$	*Mass of all bags*
C_b	*Capacity of each bag*
I_b	*Impact for 1kg of bags*

4.7.2.1.2 Indices

p	*Phase*
lc	*Life cycle*
t	*Treatments*
v	*Transportation*
s	*Sorting*
r	*Recycling*
l	*Landfill*
b	*Bag*
u	*Waste bagged*

5 CONCLUSIONS

This thesis presents a literature review and a Bibliometric analysis of the Material Flow Analysis (MFA) methodology, an inventory of the stock of residential building of the city of Rio de Janeiro, made by a new approach of the MFA; and addresses MFA combined with life cycle assessment to evaluate the impacts of construction and demolition waste.

The literature review gives understanding of development, variations and applications of the MFA methodology and also shows the participation of Brazil and Latin America in recent publications. In addition, the bibliometric analysis indicates research partnerships between groups of countries and highlights that the publications of urban metabolisms have the highest impact factors.

The present study achieved the inventory of the stock by the lifecycle approach and considered the direct variables of construction and urbanism in the building stock. Namely, the variables are intensity of materials, materials used, amount of materials and waste, total constructed area, number of buildings, number of homes, occupancy rate between different buildings in the sub regions, and stock mortality forecast.

Regarding the analysis of waste impacts, the results drew conclusions on the impacts of the types of treatments and transportation. Dumping construction and demolition waste (CDW) in landfills has dominance in impacts of WDP and, especially, HTP. The recycling of steel is extremely pollutant in all impacts, except in HTP; the class A waste recycling has high impact in GWP, CC and FDP, however, when reused, the impact is fairly low. Transport had less than 10% of participation in impacts. Therefore, the class A waste (from mortar, cement, concrete, and ceramic) recycling is desirable and important, but it is necessary to take measures to mitigate impacts GWP, CC and FDP in recycling of class A waste. Similarly, the steel recycling must have emission control and incentives for technologies that make the recycling process cleaner, for example, gas to energy transformation.

This study provides a deeper insight of the building stock, their waste flows and their impact loads and draws suggestions to underlie conscious decisions for development goals in policies to reduce their environmental impact in waste management and recycling. Moreover, it gives a good overview of MFA, which can serve systematically as an instrument for decision-making in the solid waste management plan of the city of Rio de Janeiro.

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7 SUPPLEMENTARY DATA

7.1 Chapter 3

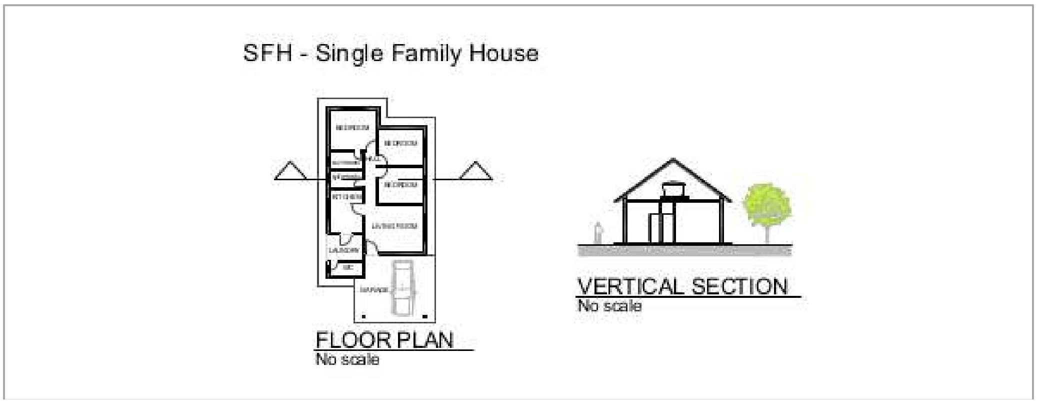

Fig. A3.1 - Plan and section of SFH

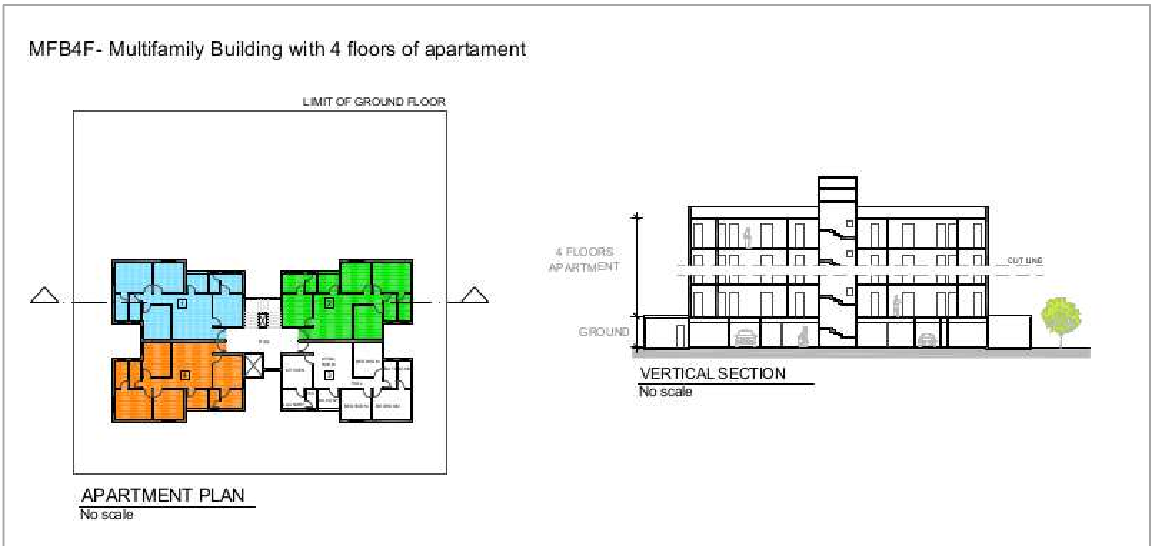

Fig. A3.2 - Plan and section of MFH-4F

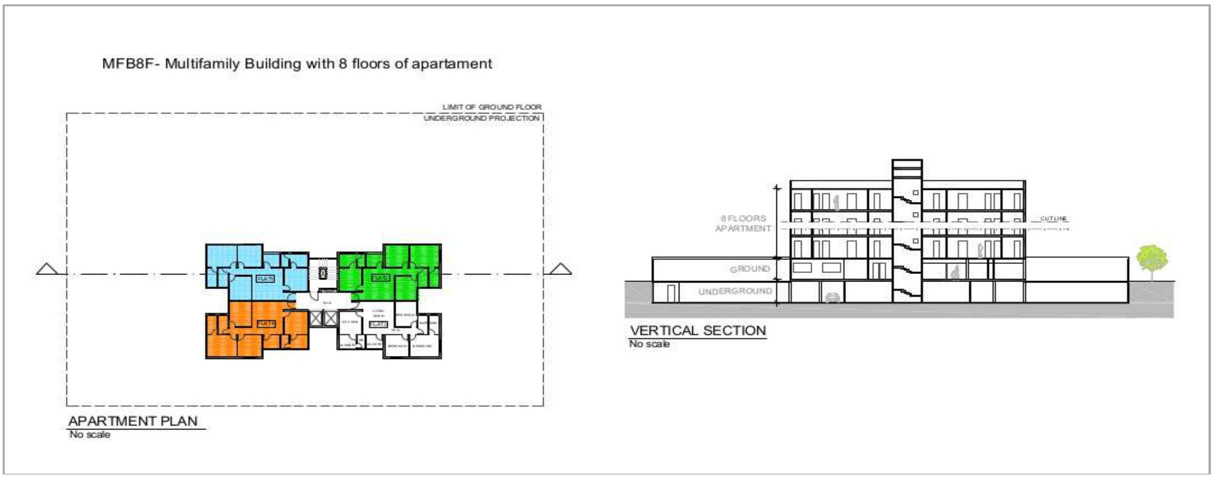

Fig. A3.3 - Plan and section of MFH-8F

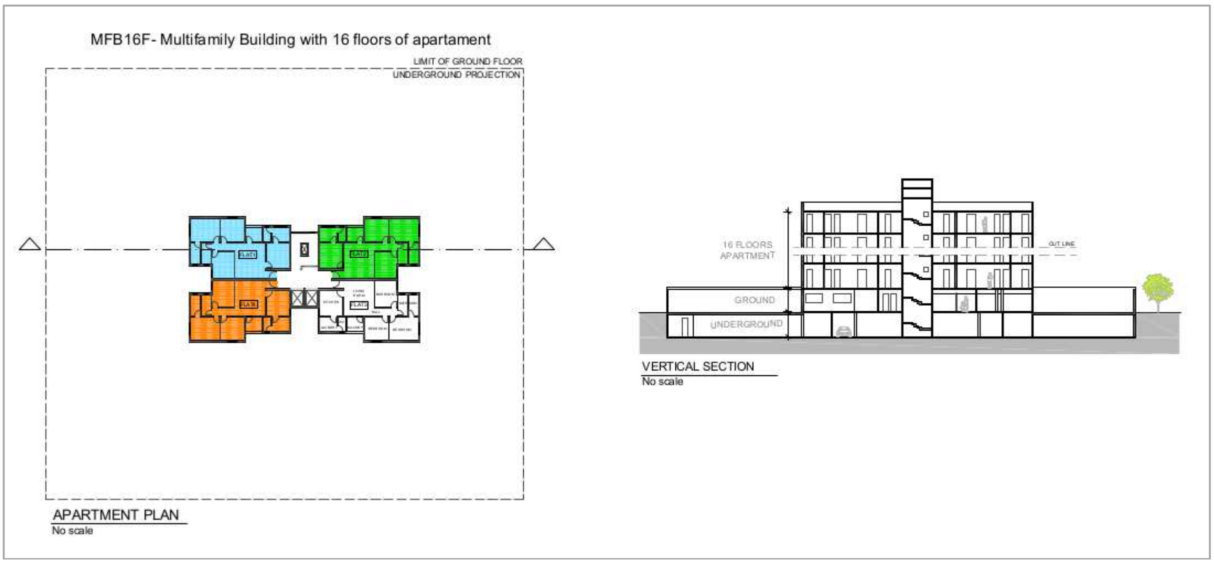

Fig. A3.4 - Plan and section of MFH-16F

Table A3.1 - Architectural design specifications

	Single Family House	Multi Family Building-4F	Multi Family Building-8F	Multi Family Building-16F
Area	107.96 m²	2,374.90 m²	5,902.93m²	10,616.20m²
Occupants	6	96	192	384
Ground floor	3 bedrooms, 3 bathrooms, kitchen, laundry, living room, hall, Parking for 2 cars	A closed area of 115.70m^2, Pilotis, Parking (32 cars), 1 function room, 1 employee´s apartment, a paved area of 1,082.00m^2	A closed area of 219.65m^2 banquet hall, a paved area of 1,995.00m^2	A closed area of 230.92m^2, 1 banquet hall, A paved area of 2,722.50m^2
Underground floor	-	-	230.92m^2 , parking for 64 cars	230.92m^2, parking for 80 cars
Apartment	-	73.21m^2 per apartment; 3 bedrooms, 3 bathrooms, kitchen, laundry, hall, balcony		
Apartment floor		323.20 m^2 per floor, 4 flats per floor, A public hall	323.20 m^2 per floor, 4 flats per floor, A public hall	323.20 m^2 per floor, 4 flats per floor, A public hall
Lift	-	1 lift	2 lifts	2 lifts
Stairs	No	Yes	Yes	Yes

Table A3.2 - Technical specifications of architectural designs and calculations parameters

Elements	SFH	MFB-4F	MFB-8F	MFB-16F
Wall	Ceramic brick board of 9x19x29cm; 16 units of brick are required for a 1m^2 wall; Each brick unit weighs 3.10kg; The ratio of the mortar is 1: 2: 8 (cement mortar, hydrated lime and sand); The thickness of the cement mortar is 20mm; The ratio of grout is 1: 3: 2 (cement mortar, hydrated lime and sand); The thickness of the grout is 5mm; The specific weight of cement= 1,200kg/m^3; The specific weight of hydrated lime= 1,700kg/m^3; The specific weight of sand= 1,700kg/m^3			
Structure [280–282]	Slab-column-beam-slab structure modelled of reinforced concrete			
Foundation [191,201,283–285] and water tank	Raft foundation	Deep foundation with Franki piling (Ø300mm)		
Roof [286]	Ceramic tiles on wood structure: On 1m^2 of roof projection0.13kg of nails; 0.19kg of brackets; 0.03m^3 of wood; 45.36kg of ceramic roof tiles; Specific weight of 795kg/m^3	Fibre cement tiles; Specific weight of 795kg/m^3; 1m^2 of the horizontal projection of the roof has 1.1 units of nails with 0.58kg and 1.24m^2 of fibre cement tiles with 25kg		
Electrical and hydro-sanitary [202,287]	Electrical: Conductor: Ø2 mm^2 and Ø4mm^2 (for electric shower and air-conditioner); The required length is based on the architectural design; Electrical feeder (3 phases, 1 neutral and 1 grounding rod): Ø16mm^2 (weight 160kg/km), 1 unit per dwelling, being 90% copper and 10% PVC; [((The vertical distance (ceiling) + horizontal path to the switchboard) *160) /1000]; Switchboard: 1 unit per dwelling (1 general 100A and 12 single poles 16A); [Note: data 4 nickel plated screws 4.2 x 19mm for fixing the frame is disregarded]; Plastic conduit: 3m (linear) /m^2 of floor; Junction box (sockets and switches): 4”x2”, being weight/unit=0.04kg; Octagonal junction box: 4”x4”, 1 unit per room, being weight: 0.067kg			
	Hydro: Cold water pipe (bathroom): PVC Ø¾” (threaded) or PVC Ø22mm (welded) and 4 meters of linear stretch per bathroom Cold water pipe (kitchen, service area): ¾” and half the linear portion of built floor Hot water pipe (bathroom): Ø½” and linear stretch 2 meters per bathroom Column cold water Bathroom: 1½” (same material as the extensions) and linear stretch of the ceiling for pavement times (how many floors of the building will have that bathroom column) Register: each bathroom: 1 valve 1”, being 0.550kg per unit Sanitary: Sewer per bathroom: 6 meters (vertical and horizontal stretch) for bathroom PVC pipe with Ø100mm, 75mm tube with 1 meter straight stretch of secondary sewage pipes and 40mm with a linear stretch of 3 meters, 1 siphon drain and 1 dry drain for bathroom Sewer per kitchen and service area: PVC pipe with Ø50mm and a linear portion of 3 meters and 1 siphon drain			

Doors and windows [191,199,287]	Aluminum and glass windows, wood doors; Windows components: Medium sand: .0049m3/un; Cement: 1.94kg/un; Aluminum frame: 1kg/m; Glass 4mm: 10kg/m². / Doors components; Medium sand 0.011m/un; Lime 1.720kg/un; Screw 1.720kg/un; Steel hinge 0.250kg/un; Steel locks: - inner 0.176kg/un; -outer 0.270kg/un; Stop timber 0.026m³/un; Piece of wood 0.003m³/un; Wood trim 0.001m3/un; Wooden door: -0.60x2.10m 22.00kg/un; -0.70x2.10m 22.00kg/un; -0.80x2.10m 27.50kg/un.
Wall, ceiling and floor linings	Ceramic tiles, PVA paint; Ceramic floor: 1.19m2 by floor area; Ceramic wall: 1.1m2, for wall area (where 2.5m² tile weighs 6,168kg); PVA paint (two layers): 0.095l /m2 (with density: 1.33–1.37g/cm³); and Acrylic paint (two layers): 0.1 l /m2 (with density: 1.14–1.18g/cm³).
Bathroom and kitchen ware and metal [199,287]	The weight found in each piece is: Steel - taps for kitchen and bathrooms: 0.5kg; - tap for laundry: 0.26kg; - sink kitchen: 0.2kg; Bathroom ware - sink: 2.9kg; - toilet: 21.0kg; sink: 6.7kg; Laundry ware - tub with column: 24.51kg;
Stones [286]	Kitchen countertop, granite Density 2,780kg/m³

Notes:

For the calculation of regular dwellings, we assume empirical trends to the construction sector in Brazil.

Often, construction of residential buildings in Brazil adheres to national rules of construction and does not follow international standards [288,289];

Inner walls consist of hollow ceramic-brick masonry, grout mortar between bricks and mortar of two layers as coating [290];

External walls do not have insulation since hollow bricks and mortar supposedly already provide the desired thermo-acoustic insulation;

Bricks are made with semi-artisanal manufacturing that still does not follow standards for high quality, minimization of material losses and prevention of the generation of greenhouse gases [288,291,292];

Mortar made of sand and cement is produced on site and applied manually by the workers on the construction site [288,293,294];

Marble and granite are widely used in Brazilian buildings for kitchen countertops, bathrooms, windowsills and doorsills.

Regarding the architectural design, some characteristics of a typical Brazilian dwelling are:

Dwellings usually have many bathrooms: a restroom, a private bathroom for at least one bedroom and one guest bathroom;

Multi-family buildings usually have a recreational area for residents and guests;

Even in popular construction, dwellings usually have a laundry room.

Regional characteristics of construction execution and architectural design influence the amount of material used in construction. Therefore, they are important variables in the estimation of material in buildings.

Table A3.3 - Amount of materialin buildings and in its elements

Element/ material	SFH %elem in building	SFH Mass of elem (kg)	SFH Mass of material (kg)	SFH %Material in elem	MFB-4F %elem in building	MFB-4F Mass of elem (kg)	MFB-4F Mass of material (kg)	MFB-4F %Material in elem	MFB-8F %elem in building	MFB-8F Mass of elem (kg)	MFB-8F Mass of material (kg)	MFB-8F %Material in elem	MFB-16F %elem in building	MFB-16F Mass of elem (kg)	MFB-16F Mass of material (kg)	MFB-16F %Material in elem
Masonry	2%	5,645.00			4%	84,384.40			3%	135,499.34			2%	135,499.34		
Cement			*68.16*	*1%*			*1,018.82*	*1%*			*1,635.96*	*1%*			*1,635.96*	*1%*
Lime			*193.11*	*3%*			*2,886.66*	*3%*			*4,635.23*	*3%*			*4,635.23*	*3%*
Sand			*772.43*	*14%*			*11,546.66*	*14%*			*18,540.92*	*14%*			*18,540.92*	*14%*
Brick			*4,611.31*	*82%*			*68,932.25*	*82%*			*110,687.22*	*82%*			*110,687.22*	*82%*
Subfloor	6%	16,291.84			1%	21,453.87			1%	46,221.83			1%	46,221.83		
Concrete			*16,291.84*	*100%*			*21,453.87*	*100%*			*46,221.83*	*100%*			*46,221.83*	*100%*
Finishes mortar	21%	53,075.38			34%	816,964.27			31%	1,538,337.20			20%	1,538,337.20		
Cement			*8,699.16*	*16%*			*148,160.55*	*18%*			*279,389.29*	*18%*			*279,389.29*	*18%*
Lime			*2,846.13*	*5%*			*43,676.31*	*5%*			*78,118.33*	*5%*			*78,118.33*	*5%*
Sand			*41,530.10*	*78%*			*625,127.41*	*77%*			*1,180,829.58*	*77%*			*1,180,829.58*	*77%*
Finishes ceramic	1%	2,028.93			2%	41,762.64			1%	27,658.05			0%	27,658.05		
Ceramic tile			*2,028.93*	*100%*			*41,762.64*	*100%*			*27,658.05*	*100%*			*27,658.05*	*100%*
Structure	66%	167,429.75			58%	1,394,603.26			64%	3,203,728.29			76%	5,958,066.38		
Concrete			*74,965.92*	*45%*			*1,303,528.43*	*93%*			*2,973,724.32*	*93%*			*5,524,611.98*	*93%*
Steel			*2,073.29*	*1%*			*48,466.80*	*3%*			*123,093.95*	*4%*			*235,379.03*	*4%*
Brick																
Wood			*90,390.54*	*54%*			*42,608.03*	*3%*			*106,910.02*	*3%*			*198,075.37*	*3%*
Roof	4%	8,935.30			0%	8,098.75			0%	8,098.75			0%	8,098.75		
Steel			*41.12*	*0%*			*18.75*	*0%*			*18.75*	*0%*			*18.75*	*0%*
Wood			*3,064.96*	*34%*												
Ceramic			*5,829.21*	*65%*												
FiberCement							*8,080.00*	*100%*			*8,080.00*	*100%*			*8,080.00*	*100%*
Door	0%	567.70			0%	10,997.76			0%	21,085.76			1%	49,959.36		
Cement			*15.48*	*3%*			*295.84*	*3%*			*5,784.42*	*27%*			*12,686.08*	*25%*
Lime			*15.48*	*3%*			*295.84*	*3%*			*552.12*	*3%*			*1,210.88*	*2%*
Sand			*162.18*	*29%*			*3,099.44*	*28%*			*552.12*	*3%*			*1,210.88*	*2%*
Steel			*17.08*	*3%*			*893.10*	*8%*			*2,488.00*	*12%*			*8,241.74*	*16%*
Wood			*357.48*	*63%*			*6,413.54*	*58%*			*11,709.10*	*56%*			*26,609.78*	*53%*
Window	0%	187.09			0%	5,700.05			0%	5,436.94			0%	12,176.72		
Medium sand			*58.31*	*31%*			*1,790.95*	*31%*			*1,849.26*	*34%*			*3,965.08*	*33%*
Cement			*13.58*	*7%*			*417.10*	*7%*			*430.68*	*8%*			*923.44*	*8%*
Aluminium frame			*29.00*	*16%*			*888.80*	*16%*			*866.70*	*16%*			*1,944.00*	*16%*
Glass 4mm			*86.20*	*46%*			*2,603.20*	*46%*			*2,290.30*	*42%*			*5,344.20*	*44%*
Hydro sanit	0%	52.29			0%	728.24			0%	1,393.72			0%	2,760.47		
Plastic			*48.29*	*92%*			*660.24*	*91%*			*1,261.72*	*91%*			*2,499.47*	*91%*
Steel			*4.00*	*8%*			*68.00*	*9%*			*132.00*	*9%*			*261.00*	*9%*
Electrical	0%	13.96			0%	133.58			0%	177.97			0%	277.74		
Cooper			*3.85*	*28%*			*56.73*	*42%*			*108.43*	*61%*			*189.20*	*68%*
Pastic			*10.12*	*72%*			*76.84*	*58%*			*69.54*	*39%*			*88.54*	*32%*
Metals	0%	5.01			0%	84.91			0%	165.07			0%	325.15		
Steel			*5.01*	*100%*			*84.91*	*100%*			*165.07*	*100%*			*325.15*	*100%*
Wares	0%	100.01			0%	1,675.66			0%	3,275.82			0%	6,483.25		
Ceramic			*100.01*	*100%*			*1,675.66*	*100%*			*3,275.82*	*100%*			*6,483.25*	*100%*
Water tank	0%	34.00														
Fiberglass			*34.00*	*100%*							-					
Stones	0%	258.13			0%	5,298.99			0%	20,676.23			1%	41,072.02		
Stones			*258.13*	*100%*			*5,298.99*	*100%*			*20,676.23*	*100%*			*41,072.02*	*100%*
		254,727.78				2,392,192.94				5,011,754.97				7,828,093.24		

Table A3.4 - Ratio of element in building type

Element	SFH	MFB-4F	MFB-8F	MFB-16F
Masonry	2.2%	3.5%	2.7%	1.7%
Subfloor	6.4%	0.9%	0.9%	0.6%
Finishes mortar	20.8%	34.2%	30.7%	19.7%
Finishes ceramic	0.0%	1.7%	0.6%	0.4%
Structure	0.0%	58.3%	63.9%	76.1%
Roof	3.5%	0.3%	0.2%	0.1%
Door	0.2%	0.5%	0.4%	0.6%
Window	0.1%	0.2%	0.1%	0.2%
Hydro sanitary	0.0%	0.0%	0.0%	0.0%
Electrical	0.0%	0.0%	0.0%	0.0%
Metals	0.0%	0.0%	0.0%	0.0%
Wares	0.0%	0.1%	0.1%	0.1%
Water tank	0.0%	0.0%	0.0%	0.0%
Stones	0.1%	0.2%	0.4%	0.5%

Table A3.5- Conciliating with the categories of buildings between model type buildings [199] , Cardeman [187], ABNT and CEF [199]

Model type buildings	Based on Cardeman	ABNT NBR 12,721:2006	CEF
SFH	Military area: story house and 2 floors house	R1 - B	CP
		R1- N	CR
		R1 - A	
		RP1Q	
MFB-4F	1+3p: access floor more 3 floors of apartment	PIS	PR
		PP4	PR (P)
		PP4 - N	
MFB-8F	1+13p: access floor more 22 floors of apartment	R8 - B	PR
		R8 - N	PR(P)
		R8 - A	
MFB-16F	1+22p: access floor more 22 floors of apartment	R16 - N	PR
	140m: total height, more than 40 floors of apartment	R16 - A	
	10.6m+puc+18p: garage floors above street level, common use for residents floor, and 18 floors of apartment		
	10.6m+puc+11/13p: garage floors above street level, common use for residents floor, and among 11 and 13 floors of apartment		

Table A3.6 - Ratio of occupation of the city and subregions by SH, SHF, MFB-4F, MFB-8F and MFB-16F

Sub region	SHF	MFB-4F	MFB-8F	MFB-16F
RJ	11%	13%	2%	73%
AP 1	0%	0%	1%	99%
AP 2	1%	0%	34%	65%
AP 3	6%	1%	0%	93%
AP 4	6%	38%	0%	56%
AP 5	30%	12%	0%	58%

Table A3.7 - Number of buildings and accomodations

	Number of buildings					Number of accommodations				
	SHF	MFB-4F	MFB-8F	MFB-16F	Total	SHF	MFB-4F	MFB-8F	MFB-16F	Total
RJ	61,616	3,525	1,921	6,694	73,756	61,616	56,399	61,477	428,441	607,933
AP1	71	0	6	413	491	71	0	208	26,450	26,728
AP2	4,136	0	1,915	2,058	8,109	4,136	0	61,270	131,729	197,134
AP3	17,517	74	0	2,672	20,263	17,517	1,180	0	171,013	189,710
AP4	9,634	2,878	0	957	13,470	9,634	46,049	0	61,271	116,954
AP5	30,257	573	0	593	31,424	30,257	9,170	0	37,979	77,406

Note: tend to be different of official numbers due calculation method

Table A3.8 - Lifetime, remaining time and number of reposition of elements

NR-Number of times of material replacement by Element in 1m² in remaining lifetime=LTE/R										
LTE (years) = Lifetime of Element										
Building type				SFH		MFB-4F		MFB-8F		MFB-16F
AGE (years)				70		60		40		20
RT (years) = remaining time of building				30		40		60		80
LTB (years)	Lifetime of Building			100		100		100		100
Element	LTE min	LTE max	LTE	NRE	LTE	NRE	LTE	NRE	LTE	NRE
Masonry	40	60	60	1	60	1	60	1	60	1
Subfloor	50	75	100	0	100	0	100	1	100	1
Finishes mortar	13	20	20	2	20	2	20	3	20	4
Finishes ceramic	13	20	20	2	20	2	20	3	20	4
Structure	50	75	75	0	75	1	75	1	75	1
Roof	13	20	20	2	20	2	20	3	30	3
Door	8	12	12	3	12	3	12	5	12	7
Window	20	30	30	1	30	1	30	2	30	3
Hydro sanit	4	6	6	5	6	7	6	10	6	13
Electrical	4	6	6	5	6	7	6	10	6	13
Metals	4	6	6	5	6	7	6	10	6	13
Wares	10	12	12	3	13	3	12	5	12	7
Water tank	8	12	12	3	12	3	12	5	12	7
Stones	13	20	20	2	20	2	20	3	20	4

Notes:

Lifetime of subfloor = Lifetime of structure

Lifetime of Roof = Lifetime of tile

Lifetime of structure is the same of the building

Table A3.9 - Material intensity from 1m^2 of buildings

Material	MI of SFH (kg/m²)	MI of MFB-4F (kg/m²)	MI of MFB-8F (kg/m²)	MI of MFB-16F (kg/m²)
Concrete	845.29	557.91	511.60	524.75
Steel / iron / aluminum / copper	20.13	21.25	21.49	23.21
Cement	81.48	63.82	48.66	28.09
Aggregate	393.88	270.14	203.59	113.46
Ceramic	116.43	50.72	23.99	13.64
Plastic	0.54	0.31	0.23	0.24
Glass	0.80	1.10	0.39	0.50
Wood	868.96	20.64	20.09	21.16
Stone	2.46	2.23	3.50	3.87
Lime	28.29	19.73	14.11	7.91
Fiberglass	0.31	0.00	0.00	0.00
Fiber cement	0.00	3.40	1.37	0.76
Total	2,358.57	1,011.26	849.03	737.60

Table A3.10 - Inflow of material table

Material	Stock MS (t)	Reposition MR (t)	Use MU (t)	Demolition MD (t)	Origin
Concrete	51,748,921	310,665	52,059,586	0	Processed material
Steel / iron / aluminum / copper	2,336,989	19,625	2,356,613	0	Processed material
Cement	3,235,132	503,600	3,738,732	0	Processed material
Aggregate	13,236,137	8,659,189	21,895,326	0	Raw material
Ceramic	1,884,120	116,495	2,000,615	0	Processed material
Plastic	23,190	107	23,297	0	Processed material
Glass	51,198	202	51,400	0	Processed material
Wood	4,311,696	142,481	4,454,176	0	Processed material
Stone	359,597	7,539	367,136	0	Processed material
Hydrated Lime	1,510,654	47,413	1,558,067	0	Processed material
Fiberglass	845	0	845	0	Processed material
Fiber cement	130,297	378	130,675	0	Processed material
Total	78,828,773	9,807,694	88,636,467		

Note: Among the aggregate, the sand is washed only, without any transformation, and therefore consider them as raw material. The crushed stone is fragmented at the place of extraction, because it has transformation of the material; it is considered as a processed material. Both are considered raw material because not transported to the industry. Steel, iron, aluminum and copper are grouped. The stones are marble and granite, which are cut in marble plants.

Table A3.11 - Geographic area, Density, characteristics of Residential building stock, Mass per area (t) (MI), Mass of estimated stock (t), Average of lifetime (years), and Potential waste (t/year) of the residential building stocks of the city of Rio de Janeiro (2010) and Austria (2003) [223].

Residential buildings in	Area (km²)	Density (inhab/km²)	Stock of residential buildings	Buildings (units)	Mass per area (t/m²)	Estimated stock (t)	Average of lifetime (years)	Potential waste (t/year)	Potential waste (%/year)
Rio de Janeiro (2010)	1,200	5,265.8	Single familiy house (2 to 4 accomodation unit)	61,616	2.58	6,923,652	100	14,475	0.2%
			Multifamily building-4floors (2 to 4 accomodation unit in each of 16 flats)	3,525	1.00	4,793,973	100	21,143	0.4%
			Multifamily building-8floors (2 to 4 accomodation unit in each of 32 flats)	1,921	0.84	8,931,200	100	30,663	0.3%
			Multifamily building-16floors (2 to 4 accomodation unit in each of 64 flats)	6,694	0.74	58,179,949	100	83,600	0.1%
			Total	73,756		78,828,773		149,880	
Austria (2003)	83,879	101.4	1 or 2 accomodation units	1,553,000	2.3	405,000,000	100	4,050,000	1.0%
			3 to 10	694,999	2.3	117,000,000	100	1,170,000	1.0%
			11 and more	977,000	2.3	150,000,000	100	1,500,000	1.0%
			Total	2,247,999		522,000,000		5,220,000	

Table A3.12 - Ratio of buildings (unit), Material intensities (t per building) of concrete and other construction minerals of residential buildings sotck of the city of Rio de Janeiro in 2010 and Northern Europe in 2003, Central Europe in 2003 and Southern Europe in in 2003

Region (year)	Characteristic	Single family house	Multi-family buildings	High-size buildings (12 or more floors)
Rio de Janeiro City (2010)	Ratio of buildings	83.5%	7.4%	9.1%
	Material intensities (t per building):			
	Concrete	91	4,345	5,571
	Other construction minerals	55	756	1,346
Northern Europe, EU25 (2003)	Ratio of buildings	92%	7%	1%
	Material intensities (t per building):			
	Concrete	119	1,493	3,627
	Other construction minerals	220	994	1,058
Central Europe, EU25 (2003)	Ratio of buildings	94%	6%	0%
	Material intensities (t per building):			
	Concrete	119	1,257	2,936
	Other construction minerals	186	1,001	807
Southern Europe, EU25 (2003)	Ratio of buildings	89%	11%	0%
	Material intensities (t per building):			
	Concrete	142	1,198	2,936
	Other construction minerals	129	654	1,449

7.2 Chapter 4

Table A4.1 - Mass of waste generated between 2010 and 2013 from materials types, considering building types and sub regions

2010-2013					
	SFH (t)	MFB-4F (t)	MFB-8F (t)	MFB-16F (t)	Total (t)
Concrete from AP1	7.72	2.81	0.08	26.29	36.90
Concrete from AP2	0.01	0.00	0.09	363.36	363.47
Concrete from AP3	0.77	0.00	129.76	141.30	271.83
Concrete from AP4	10.05	0.02	0.00	172.63	182.70
Concrete from AP5	5.18	55.29	0.00	37.73	98.19
Concrete from RJ					**953.08**
Steel from AP1	0.01	0.07	0.00	2.22	2.30
Steel from AP2	0.00	0.00	0.00	30.64	30.65
Steel from AP3	0.00	0.00	3.59	11.92	15.51
Steel from AP4	0.01	0.00	0.00	14.56	14.57
Steel from AP5	0.00	1.37	0.00	3.18	4.56
Steel from RJ					**67.58**
Cement from AP1	1.98	3.71	0.25	45.59	51.53
Cement from AP2	0.00	0.00	0.28	630.22	630.51
Cement from AP3	0.20	0.00	384.05	245.07	629.32
Cement from AP4	2.58	0.03	0.00	299.42	302.03
Cement from AP5	1.33	73.11	0.00	65.43	139.87
Cement from RJ					**1,753.25**
Aggregates from AP1	45.36	196.37	4.17	717.67	963.57
Aggregates from AP2	0.09	0.00	4.76	9,920.19	9,925.03
Aggregates from AP3	4.54	0.00	6,505.74	3,857.63	10,367.91
Aggregates from AP4	59.04	1.49	0.00	4,713.14	4,773.67
Aggregates from AP5	30.40	3,869.11	0.00	1,029.97	4,929.48
Aggregates from RJ					**30,959.67**
Ceramic from AP1	3.03	8.61	0.06	5.07	16.77
Ceramic from AP2	0.01	0.00	0.06	70.10	70.17
Ceramic from AP3	0.30	0.00	88.02	27.26	115.59
Ceramic from AP4	3.94	0.07	0.00	33.31	37.31
Ceramic from AP5	2.03	169.70	0.00	7.28	179.01
Ceramic from RJ					**418.86**

Table A4.2 - Mass of waste generated between 2014 and the buildings demolition from materials types, considering buildings types and sub regions

2014-Demolition					
	SFH (t)	MFB-4F (t)	MFB-8F (t)	MFB-16F (t)	Total (t)
Concrete from AP1	8,768.51	1,312.91	310.87	8,921.91	19,314.21
Concrete from AP2	1,049.09	0.00	916.33	91,426.79	93,392.21
Concrete from AP3	7,268.20	0.00	32,015.40	54,175.94	93,459.53
Concrete from AP4	20,205.37	231.52	0.00	46,129.09	66,565.98
Concrete from AP5	11,213.97	9,064.40	0.00	16,701.71	36,980.08
Concrete from RJ					**309,712.00**
Steel from AP1	7.62	32.62	8.61	752.42	801.28
Steel from AP2	0.91	0.00	25.38	7,710.41	7,736.71
Steel from AP3	6.32	0.00	886.78	4,568.89	5,461.99
Steel from AP4	17.57	5.75	0.00	3,890.26	3,913.58
Steel from AP5	9.75	225.22	0.00	1,408.53	1,643.50
Steel from RJ					**19,557.06**
Cement from AP1	2,247.99	1,736.01	920.13	15,474.62	20,378.75
Cement from AP2	268.96	0.00	2,712.15	158,575.28	161,556.38
Cement from AP3	1,863.36	0.00	94,759.23	93,965.50	190,588.09
Cement from AP4	5,180.07	306.12	0.00	80,008.63	85,494.83
Cement from AP5	2,874.94	11,985.50	0.00	28,968.30	43,828.74
Cement from RJ					**501,846.79**
Aggregates from AP1	51,511.28	91,876.98	15,586.77	243,582.28	402,557.31
Aggregates from AP2	6,162.96	0.00	45,943.34	2,496,095.14	2,548,201.44
Aggregates from AP3	42,697.60	0.00	1,605,204.73	1,479,088.28	3,126,990.61
Aggregates from AP4	118,698.07	16,201.35	0.00	1,259,396.61	1,394,296.03
Aggregates from AP5	65,877.35	634,323.43	0.00	455,982.97	1,156,183.75
Aggregates from RJ					**8,628,229.15**
Ceramic from AP1	3,439.87	4,029.86	210.89	1,721.31	9,401.93
Ceramic from AP2	411.56	0.00	621.61	17,638.98	18,672.14
Ceramic from AP3	2,851.30	0.00	21,718.22	10,452.17	35,021.69
Ceramic from AP4	7,926.54	710.62	0.00	8,899.69	17,536.84
Ceramic from AP5	4,399.23	27,822.37	0.00	3,222.26	35,443.86
Ceramic from RJ					**116,076.46**

Table A4.3 - Mass of waste generated in buildings demolitions from materials types, considering buildings types and sub regions

Demolition					
	SFH (t)	MFB-4F (t)	MFB-8F (t)	MFB-16F (t)	Total (t)
Concrete from AP1	409,986.33	327,960.14	50,324.49	1,699,488.85	2,487,760
Concrete from AP2	49,009.46	0.00	148,311.39	17,433,262.87	17,630,584
Concrete from AP3	339,573.91	0.00	5,202,283.10	10,316,212.19	15,858,069
Concrete from AP4	944,374.61	57,713.63	0.00	8,793,863.84	9,795,952
Concrete from AP5	524,108.52	2,273,206.15	0.00	3,179,241.04	5,976,556
Concrete from RJ					**51,748,921**
Steel from AP1	10,306.50	13,187.66	2,231.67	79,331.82	105,058
Steel from AP2	1,232.03	0.00	6,576.96	813,781.41	821,590
Steel from AP3	8,536.43	0.00	230,698.47	481,558.83	720,794
Steel from AP4	23,740.30	2,320.73	0.00	410,495.90	436,557
Steel from AP5	13,175.38	91,408.28	0.00	148,406.37	252,990
Steel from RJ					**2,336,989**
Cement from AP1	39,212.54	37,263.55	4,759.32	90,485.07	171,720
Cement from AP2	4,687.44	0.00	14,026.21	928,190.87	946,905
Cement from AP3	32,478.05	0.00	491,993.84	549,261.15	1,073,733
Cement from AP4	90,323.33	6,557.55	0.00	468,207.49	565,088
Cement from AP5	50,127.59	258,286.70	0.00	169,270.81	477,685
Cement from RJ					**3,235,132**
Aggregates from AP1	187,569.47	155,942.25	19,717.40	361,813.56	725,043
Aggregates from AP2	22,421.91	0.00	58,109.19	3,711,463.51	3,791,995
Aggregates from AP3	155,355.67	0.00	2,038,282.19	2,196,275.33	4,389,913
Aggregates from AP4	432,053.07	27,442.34	0.00	1,872,174.19	2,331,670
Aggregates from AP5	239,780.58	1,080,890.17	0.00	676,846.16	1,997,517
Aggregates from RJ					**13,236,137**
Ceramic from AP1	56,469.84	29,813.97	2,359.98	44,182.70	132,826
Ceramic from AP2	6,750.36	0.00	6,955.10	453,223.68	466,929
Ceramic from AP3	46,771.52	0.00	243,962.31	268,197.16	558,931
Ceramic from AP4	130,074.29	5,246.59	0.00	228,619.70	363,941
Ceramic from AP5	72,188.56	206,651.01	0.00	82,652.76	361,492
Ceramic from RJ					**1,884,120**

Table A4.4 - Distances between sub regions and destiny in scenario as 2010

			From buildings to			
			Caju	**Gericinó**	**Seropédica**	
Sub region	**Weight***	**Local: reference point (Lat, Long)**	-22.879952, -43.224848	-22.842719, -43.475539	-22.793591, -43.761136	
AP1	5%	-22.904618, -43.190132	7	41	116	Distance (km)
AP2	35%	-22.964248, -43.217534	12	48	121	Distance (km)
AP3	31%	-22.839167, -43.311519	21	24	90	Distance (km)
AP4	19%	-22.980643, -43.409249	34	41	77	Distance (km)
AP5	11%	-22.903103, -43.567788	51	18	31	Distance (km)
			23	**36**	**93**	**Weighted average of Distances (km)**

Note:
*Weight by sub region based on the mass (TCA)

Table A4.5 - Local reference points of sub region of origin and the destinations of the waste and the treated material [207]

Origin/Destiny	**Treatment**	**Coordinates (Lat/Long)**
Sub region AP1	Demolition	-22.904618, -43.190132
Sub region AP2	Demolition	-22.964248, -43.217534
Sub region AP3	Demolition	-22.839167, -43.311519
Sub region AP4	Demolition	-22.980643, -43.409249
Sub region AP5	Demolition	-22.903103, -43.567788
Missões	Recycling	-22.804629, -43.289693
Caju	Sorting	-22.879952, -43.224848
Gramacho	Landfill	-22.672075, -43.252757
Gericinó	Landfill	-22.842719, -43.475539
Seropédica	Landfill	-22.793591, -43.761136
(I) Arco da aliança	Sorting and recycling	-22.907730, -43.309246
(II) Industria extrativa e comercial pop ltda me	Sorting and recycling	-22.739391, -43.494824
(III) Pedreira copacabana ltda	Sorting and recycling	-22.929001, -43.403426
(IV) Tamoio mineração s.a.	Sorting and recycling	-22.930517, 43.401712
(V) Concretran s.a.	Sorting and recycling	-22.861936, -43.288242
(VI) Mineração galácia ltda	Sorting and recycling	-22.884184, -43.658533
(VII) Solução gerenciamento de resíduos ltda. Me	Sorting and recycling	-22.883462, -43.260077
Thyssenkrupp CSA Siderúrgica do Atlântico	Recycling (steel plant)	-22.907198, -43.736057

Table A4.6 - Distances between sub regions and intermediate destinations in scenario as from 2014.

	Company								
Sub region	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	Median of distance until the companies	Weight by sub region based on the mass (TCA)
AP1	19	42	30	30	16	57	11	30	5%
AP2	24	48	35	33	20	64	19	33	35%
AP3	16	25	15	21	7	40	18	19	31%
AP4	19	59	15	15	27	45	16	19	19%
AP5	47	53	30	32	37	13	56	40	11%
								Weighted average of distance (km)	27

Table A4.7 - Distances between intermediate and final destinations in scenario as from 2014.

Intermediate destiny			**Final destiny**							
Sorting and Recycling			**Landfill**		**Reuse of concrete, cement, aggregates and ceramic**				**Reuse of steel in industry**	
Companies			**Gericinó**	**Seropédica**	**Companies and builders**				**Industries**	
	Rate of receipt		23%	4%	71%		Rate of receipt		2%	
	100.0%	Coordinates (Lat/Long)	-22.842719, -43.475539	-22.793591, -43.761136		Coordinates (Lat/Long)				Coordinates (Lat/Long)
			Distance (km)	Distance (km)	Distance (km)				Distance (km)	
(I)	14.3%	-22.907730, -43.309246	32	88	17	-22.929001, -43.403426	10.4%	**(III)**	54	-22.907198, -43.736057
(II)	14.3%	-22.739391, -43.494824	40	41	0	-22.739391, -43.494824	10.4%	**(II)**	67	-22.907198, -43.736058
(III)	14.3%	-22.929001, -43.403426	21	69	0	-22.929001, -43.403426	10.4%	**(III)**	46	-22.907198, -43.736059
(IV)	14.3%	-22.930573, -43.401741	20	68	0	-22.930573, -43.401741	10.4%	**(IV)**	47	-22.907198, -43.736060
(V)	14.3%	-22.861936, -43.288242	35	96	0	-22.861936, -43.288242	10.4%	**(V)**	53	-22.907198, -43.736061
(VI)	14.3%	-22.884184, -43.658533	24	20	0	-22.884184, -43.658533	10.4%	**(VI)**	10	-22.907198, -43.736062
(VII)	14.3%	-22.883462, -43.260077	33	99	20	(variable)	10.4%		56	-22.907198, -43.736063
		Average	**29**	**69**	**5**				**47**	

7 APPENDICES

7.1 Publications

7.1.1 Journal articles

7.1.1.1 Manuscripts published

Condeixa, K., Haddad, A., Boer, D., 2014. Life Cycle Impact Assessment of masonry system as inner walls: A case study in Brazil. Constr. Build. Mater. 70, 141–147. doi:10.1016/j.conbuildmat.2014.07.113

Condeixa, K., Qualharini, E., Boer, D., Haddad, A., 2015. An Inquiry into the Life Cycle of Systems of Inner Walls: Comparison of Masonry and Drywall. Sustainability 7, 7904–7925. doi:10.3390/su7067904

Haddad, A.N., Condeixa, K., Sedrez, M., Evangelista, A.C.J., Boer, D.T., Catarina, A., Boer, D.T., 2013. Quality Indicators for Life Cycle Inventory: Real Cases Exploratory Application. Appl. Mech. Mater. 431, 350–355. doi:10.4028/www.scientific.net/AMM.431.350

Haddad, A.N., de Moraes Sedrez, M., de Macedo Pires Condeixa, K., Evangelista, A.C.J., Boer, D.T., 2013. Life Cycle Assessment: A Comparison of Ceramic Brick Inventories to Subsidize the Development of Databases in Brazil. Appl. Mech. Mater. 431, 370–377. doi:10.4028/www.scientific.net/AMM.431.370

7.1.1.2 Manuscripts submitted

Condeixa, K., Haddad, A., Boer, D., 2016. Material Flow Analysis of the Residential Building Stock at the city of Rio de Janeiro. Journal of Cleaner Production.

7.1.1.3 Manuscripts in progress

Condeixa, K., Haddad, A., Boer, D., 2016. Material Flow Analysis combined with Life Cycle Impact Assessment for the evaluation of waste flows from the building stock. Journal of Cleaner Production.

Condeixa, K., Haddad, A., Boer, D., 2016. Literature review and bibliometric analysis for supporting the systematic use of Material Flow Analysis. Environmental Impact Assessment Review.