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# Material Stock Data Extraction using Geographic Imagery in Material Flow Analysis for Urban Infrastructure

Muhammad Imran

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de doctorat  
de l'UTT

**Muhammad IMRAN**

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using Geographic Imagery  
in Material Flow Analysis  
for Urban Infrastructure**

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# THESE

*pour l'obtention du grade de*

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*présentée et soutenue par*

**Muhammad IMRAN**

*le 26 juin 2020*

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**Material Stock Data Extraction using Geographic Imagery  
in Material Flow Analysis for Urban Infrastructure**

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*This research work is dedicated to .....*

*My Wonderful and Kind Parents,*

*Dr. & Mrs Abdul Waheed,*

*who blessed me with all their love and prayers and facilitated me in all the needs and comforts through their utmost care, efforts and sacrifices.*

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*Khoula Imran,*

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*Shabnam Apa & Sadia,*

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**Muhammad Imran**



# ABSTRACT

Material Flow Analysis (MFA) is a powerful tool to track and estimate material flows and stocks of resources and evaluate the efficiency of the materials used in the modern infrastructure. Various industries (for example, iron and steel industry, construction industry, transportation etc.) have been applying MFA extensively. However, the use of MFA is limited largely due to the lack of regional data, uncertainty in the available data and lack of input data at all in some cases. Several studies have applied various secondary or complementary methods, such as Geographic Information System (GIS) and Nighttime Light Satellite Imagery so that data limitation for MFA is addressed but with a limited success except for few sectors (e.g., building and construction sectors).

In this study, we address this issue by employing Google Earth as a secondary method that can potentially extract data applicable to material flow analysis. This data collection approach is applied on French Railway Infrastructure by systematically selecting 95 railway tracks (20% of the total number of tracks) covering more than 9000 km of track length (~31% of the total) and verified results with the official SNCF data based upon the developed parameters. Furthermore, the extracted data has been used for the estimation of metallic (steel) and non-metallic (wood and aggregate) material stocks in the covered portion of the French railway system. This study thus contributes to overcome data issues of MFA and accelerate the application of MFA on a wider scale.

**Keywords:** Urban metabolism, Inventories, Geographic information systems, Railroads, Railroads--buildings and structures, Google Earth

## **ABSTRACT (Version Français)**

L'analyse des flux de matériaux (AFM) est un outil puissant pour suivre et estimer les flux de matériaux et les stocks de ressources et évaluer l'efficacité des matériaux utilisés dans les infrastructures modernes. Diverses industries (par exemple, industrie sidérurgique, industrie de la construction, transports, etc.) ont largement appliqué l'AFM. Cependant, l'utilisation de l'AFM est limitée en grande partie en raison du manque de données régionales, de l'incertitude dans les données disponibles et du manque de données d'entrée dans certains cas. Plusieurs études ont appliqué diverses méthodes secondaires ou complémentaires, telles que le système d'information géographique (SIG) et l'imagerie satellite de lumière nocturne afin que la limitation des données pour l'AFM soit abordée, mais avec un succès limité, à l'exception de quelques secteurs (par exemple, les secteurs du bâtiment et de la construction).

Dans cette étude, nous abordons ce problème en utilisant Google Earth comme méthode secondaire pouvant potentiellement extraire des données applicables à l'analyse des flux de matières. Cette approche de collecte des données est appliquée sur les infrastructures ferroviaires françaises en sélectionnant systématiquement 95 voies ferrées (20% du nombre total de voies) couvrant plus de 9000 km de longueur de voie (~ 31% du total) et des résultats vérifiés avec les données officielles de la SNCF sur les paramètres développés. En outre, les données extraites ont été utilisées pour estimer les stocks de matériaux métalliques (acier) et non métalliques (bois et granulats) dans la partie couverte du réseau ferroviaire français. Cette étude contribue ainsi à surmonter les problèmes de données de l'AFM et à accélérer l'application de l'AFM à plus grande échelle.

**Mots Clés:** métabolisme urbain, stocks, systèmes d'information géographique, chemins de fer, infrastructures ferroviaires, Google Earth

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# LIST OF ABBREVIATIONS

<b>MFA</b>	Material Flow Analysis
<b>US</b>	United States
<b>UK</b>	United Kingdom
<b>EU</b>	European Union
<b>SDG</b>	Sustainable Development Goal
<b>GIS</b>	Geographic Information System
<b>ASCE</b>	American Society of Civil Engineers
<b>LCA</b>	Life Cycle Assessment
<b>NTL</b>	Nighttime Light
<b>S-NPP VIIRS</b>	Suomi National Polar-orbiting Partnership's Visible Infrared Imaging Radiometer Suite
<b>DMSP-OLS</b>	Defense Meteorological Satellite Program's Operational Linescan System
<b>GDP</b>	Gross Domestic Product
<b>Gt</b>	Gigatons
<b>Kt</b>	Kiloton
<b>SNCF</b>	Société Nationale des Chemins de fer Français
<b>LGV</b>	Ligne à Grande Vitesse (High-Speed Line)
<b>TGV</b>	Train à Grande Vitesse (High-Speed Train)
<b>UIC</b>	International Union of Railways
<b>GUI</b>	Graphic User Interface
<b>SD</b>	Sleeper Density

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# NOMENCLATURE

<b>K<sub>BS</sub></b>	Kilometer per bridge for SNCF Data, The average distance in kilometers between two bridges as per SNCF statistical data.
<b>K<sub>BG</sub></b>	Kilometer per bridge for Google Earth Data, The average distance in kilometers between two bridges as per Google Earth extracted data.
<b>K<sub>LS</sub></b>	Kilometer per level crossing for SNCF Data, The average distance in kilometers between two level crossings as per SNCF statistical data.
<b>K<sub>LG</sub></b>	Kilometer per level crossing for Google Earth Data, The average distance in kilometers between two level crossings as per Google Earth extracted data.
<b>Single Line</b>	A railway line running as a single way track.
<b>Double Line</b>	A railway line running as a two-way track.
<b>Multiple Line</b>	A railway line running as more than two-way track.
<b>Track Multiplicity</b>	The number of railway lines running parallel to each other over a certain length.
<b>Class-A Track</b>	A railway line measuring more than 300 kilometers in length from its origin to the destination.

<b>Class-B Track</b>	A railway line measuring from 100 to 300 kilometers in length from its origin to the destination.
<b>Class-C Track</b>	A railway line measuring less than 100 kilometers in length from its origin to the destination.
<b>Graphic User Interface (GUI)</b>	An interface which allows the user to interact with the electronic device through icons, indicators, commands etc.



## **CHAPTER 1**

# **INTRODUCTION**

The human population is on a constant rise, and so is economic growth. Since the start of the twentieth century, there is an ever-increasing need for necessary urban infrastructure to keep the society run and economy to function. The urban structure, in turn, consumes many limited natural resources. This limitation forces humankind to devise policies on extraction, production, use, recycling, reuse, and disposal of the materials. These materials are input to the urban infrastructure, and they generate waste as system output. The material that gets stored in the infrastructure becomes stock, and that stays there. Some tools and methods are used for material balance evaluation to make policy decisions to keep inputs, outputs, and stocks in check. Material Flow Analysis (MFA) is one such tool that is employed globally for this purpose. Along with many strengths and benefits that MFA has, it also has some issues which have been explored in this research work, and a solution has also been proposed. Chapter 1 provides the basic insight of this research work and gives a general perspective of the MFA, its shortcomings and prospects of use of other methods to address them. At the end of this chapter, a brief outline of the chapters has also been given, which enables the reader to fathom the interrelation and continuity of the chapters.

## **1.1. Global Perspective of Modern Infrastructure and Material Accounting**

The 20<sup>th</sup> century has seen an unprecedented rise in population throughout the World. In the last one hundred years, the human population has increased four times than what it was at the start of the twentieth century (Krausmann et al., 2009). Currently, the population of the world stands at 7.7 billion, and it is expected that it will be around 8.5 billion in 2030, 9.7 billion in 2050 and 10.9 billion in 2100 (United Nations, 2019; Pison, 2019). Similarly, global economic growth has also been increased 20 times in the last century (Swilling, 2011; Maddison, 2007). This population expansion and enormous global economic growth gave rise to urbanization, and the small cities started to grow outward. Cities grow in a very complicated way based upon size, economic, political policies, and social structures (Kennedy et al., 2007).

To accommodate an ever-increasing population within a relatively small space of the cities, it required the development of large and efficient infrastructure systems that could sustain the present and future society. The development of substantial infrastructural systems included buildings, roads, railways, harbours, airways, communication, and other auxiliary networks and structures that are a basic need for a society to function and run. This enormous infrastructure build-up gave rise to a new era of the world called Anthropocene (Lucy, 2019). The term Anthropocene is a nomination for a new geological earthly era. It includes the period in which the man has become one of the most important influencing factors on the biological, geological, and atmospheric processes on earth. This new era added another sphere into the Earth's atmosphere called Anthroposphere. The Anthroposphere (sometimes also referred to as technosphere) is that part of the environment that is made or modified by humans for use in human activities and human habitats (Jan, 2019).

Around 50 years ago, in 1965, Abel Wolman coined the term Urban Metabolism and pioneered a revolutionary concept in which he compared a city to a living organism. He argued that just like a living organism has inputs, outputs, and stocks of the materials and the

energy, in the same manner, a city can have its metabolism. He applied this concept to a hypothetical American city of one million inhabitants and estimated the flows of energy, water, materials, and wastes in and out of that city (Wolman, 1965; Kennedy, 2007).

By now, there exist several methodologies that can be applied to describe the metabolic process of cities, regions, and nations. One of those methods is Material Flow Analysis (MFA), which has been successfully applied in resource management, waste management, environmental management, and other alike fields (Brunner & Rechberger, 2016).

### **1.2. Material Flow Analysis (MFA) and Its Application in Stock and Flow Estimation**

Material flow analysis (MFA) is a useful tool to systematically assess flows and stocks of a given material within certain geographic and temporal system boundaries. In the fields of resource management, waste management, and environmental management, this method is very beneficial in estimating the flow of materials and evaluate the efficiency of the materials (Takahiro et al., 2009; Brunner & Rechberger, 2016). MFA studies have three primary objectives: 1) identify material flows and stocks, 2) contextualize and interpret the flow and stock, and 3) recommend relevant policies for optimal resource efficiency (Hendriks et al., 2000).

In MFA, mainly, there are two approaches in use; 1) Top-down approach, 2) Bottom-up approach. The top-down approach uses annual time-series statistical data for material production to estimate material stocks, whereas the bottom-up approach the number of products within the specific boundary are quantified, and then material intensities of these products are multiplied with the number of products to estimate the material stocks (Takahiro, 2009; Paul, 2004).

Many studies have already been conducted to determine the flows of various materials, e.g. copper, silver, chromium, iron, lead, steel, nickel, and aluminium in the US, Europe, and Japan (Kazue, 2009). Many studies have been carried out for building and transportation



infrastructures for determining stocks present in the anthropogenic sphere. Within transportation infrastructures, the road infrastructure has been studied by numerous studies in the US and Europe (Wiedenhofer, 2015; Miatto, 2017).

### **1.3. Data Issues Related to MFA**

Although MFA approaches like the bottom-up flow and top-down flow work very well on a national or global scale, however, these fail to give good results on a regional level since there is rarely any material trade or consumption data available (Bailang, 2018). In developing countries where public data statistics are not well organized or less frequently available, data related to in-use stock is even challenging to find (Kazue, 2009). Developing countries like China, Russia, and India have an extensive stock of steel they lack in statistical data availability (Feng-Chi, 2011).

Apart from data limitations generally mentioned in the literature, the following studies have explicitly discussed this problem in detail.

Patricio (2015) shows how to input data collection affects MFA results. Using time-series MFA data for 1996-2011 on three spatial levels, i.e. national (Sweden); regional (Stockholm region) and metropolitan (Stockholm, Gothenburg, and Malmo), it was depicted that how the quality of input data and errors in input data affect the overall results. They concluded that as the spatial level is decreased from national to regional and metropolitan levels, the data availability lowers as well.

(Laner, 2015)Laner (2015) studied on MFA input data uncertainty for plastic flows in Austria. They insisted that there exists a certain degree of lack of information about MFA data input irrespective of the level of sophistication is adopted in the approach since material flows are specific for a particular geographical region, time frame and the material. The appropriate data for the actual system being studied may often not be available. Hence, data corresponding to the proposed method is derived from up- and downscaling using a transformation of data reported for other similar systems, or using expert judgment.

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Data that supports MFA is mostly available for developed countries. European Union (EU) and other developed countries have documented a sufficient level of data for conducting MFA and integrated it as a core component of environmental accounting to provide evidence-based policy decisions (Vilaysouk et al. 2017). For example, the Sound Material Cycle Society in Japan applied three indicators for reaching social high-level policy objectives, which are derived from MFA. European Commission developed Resource Efficiency Scoreboard to track advancement towards increased resource efficiency in the member states. Also, the Group of Seven (G7) countries devised a new initiative to integrate resource management and economic policy in one framework.

Implementation and monitoring progress of Sustainable Development Goals (SDGs), addressing resource productivity, management, and efficiency, are mentioned as critical needs for the developing countries to ensure timely and affordable natural resource provision. Baninla et al. (2019) show that mineral productivity is low in Africa and Asian countries compared to developed nations. Although MFA approaches like the bottom-up flow and top-down flow work very well on a national or global scale, however, these fail to give good results on a regional level since there is rarely any material trade or consumption data available (Bailang, 2018).

As opposed to critical information needs, developing countries also lack institutional capacity, financial resources, and human capital for statistic reporting. On the one hand, developing countries need information collection techniques suitable for their limited capacity and resources; on the other hand, monitoring and documentation systems need to be put in place. For example, many studies applied international databases, still, those seem not entirely relevant to socio-economic characteristics of developing countries such as informal economic activities, different industrial systems, and underreporting trends (Vilaysouk et al. 2017).

Data acquisition for conducting MFA is complicated and thus is expanded to include informal sources, including market research, expert judgment, best scenarios and other ‘hands-on’ knowledge (Rahman et al. 2019). Furthermore, beyond national and international statistical

databases, secondary, and complementary data collection techniques are also used in different studies recently (Bailang et al. 2018).

#### **1.4. Application of Secondary Methods to Address Data Deficiency in MFA**

To overcome such data collection shortcomings that arise due to less or no availability of compiled statistical data at a national, regional, or global scale, some other complementary methods are required to be employed for better estimation and understanding of stocks and flows. A few studies have been conducted in which secondary methods such as Satellite Imagery Programs, Geographic Information System (GIS), Nighttime Light and Remote Sensing have been employed to address the data deficiency in estimating stocks and flows.

Table 1.1 summarizes the studies, which applied secondary methods to complement the MFA data limitation issues. A detailed overview of the studies mentioned in the Table 1.1 and some other studies have been presented in Chapter 2 of this research work, and a detailed analysis of their use, feasibility, benefits, and shortcomings have also been conducted.

#### **1.5. Scope of Satellite Imagery Program ‘Google Earth’ for Material Stock Data Extraction in MFA**

The secondary methods, which have previously been applied along with MFA, are mainly dependent on GIS or nighttime light (Hattori, 2014; Bailang, 2018; Tanikawa, 2009). However, these approaches are limited in their sector-specific application. For example, the nighttime image only takes into account the urban part of a geographic region and fails to take into account the material stocks in the rural region (Bennett, 2017). This approach may take good care of steel or copper stock of building infrastructure in urban areas while failing to consider the steel stocks in the railway infrastructure located in the rural zones. On the other hand, methods based on GIS help coping with the issues related to sector-specific applications, but are not that accurate on a precise volume of the structures since these methods help take linear dimensions but fail to take vertical measurements (Fritz, 2016).

**Table 1.1. Studies conducted using MFA with the help of secondary methods**

<b>Sr. No.</b>	<b>Studies</b>	<b>Purpose</b>	<b>Secondary Method</b>	<b>Material/Domain</b>
1.	Bailang Yu et. al. (2018)	Spatial-Temporal Dynamics of Global Anthropogenic Resources Accumulation above Ground	Nighttime Light Images	Global anthropogenic stocks
2.	Hanwei Liang et. al. (2017)	Estimation of in-use steel stock of buildings and civil engineering infrastructures	Nighttime Light Data	Steel stock, buildings
3.	Fritz Kleemann et. al. (2016)	Analysis of Vienna's Material Stock in Buildings	GIS	Building stock
4.	Hiroki Tanikawa et. al. (2015)	A Comprehensive Account of the Construction Material Stock of Japan	GIS	Construction material stock
5.	Tomer Fishman et. al. (2015)	The socio-economic drivers of material stock accumulation in Japan's prefectures	GIS	Material stock
6.	Hanwei Liang et. al. (2014)	Modeling In-Use Steel Stock in China's Buildings and Civil Engineering Infrastructure	Nighttime Lights	In-use steel stock, Buildings
7.	Ryoma Hattoria et. al. (2014)	Estimation of in-use steel stock for civil engineering and building	Nighttime Light Images	In-Use steel stock, Buildings
8.	Feng-Chi Hsu et. al. (2013)	Estimating in-use steel stocks in civil engineering and buildings	Nighttime Lights	In-use steel stock, Buildings
9.	Feng-Chi Hsu, et. al. (2011)	Estimation of Steel Stock in Building and Civil Construction	Satellite Images	Steel stocks, buildings
10.	Kazue Takahashi et. al. (2009)	Analysis of In-Use Stock of Copper	Satellite Nighttime Light	In-use copper stock
11.	Hiroki Tanikawa et. al. (2009)	Spatial material stock analysis	GIS	Building stock

Furthermore, these methods are very useful in determining economic growth, business activities, land occupancy, building infrastructure, and electricity consumption for developed countries. Unfortunately, in developing and underdeveloped countries, there is a lack of availability of electricity in the majority of the areas. In some of those countries, urbanization is also not that well spread (Bennett, 2017; Goldstein, 2017). Hence, such methods are not suitable for those countries.

These methods are also good indicators of in-use stocks in building infrastructures, which are usually provided with the electricity, whereas for the transportation sector in general and railway network infrastructure, in particular, lacks this facility. Another issue is that instead of direct observation or input data collection, these approaches heavily rely on empirical relationships or correlations, which involves several uncertainties.

It is, therefore, necessary to include a more comprehensive and easily accessible data collection process that helps apply MFA in the developing countries. It may well assist in data extraction on a regional basis. In light of this discussion, we propose to use *Google Earth* as a solution to limitations and uncertainties in data collection. It is feasible to obtain in-use material stock data in developed as well as developing countries at the city, regional, national or global level. It becomes possible by capturing all measurements (length, width, height) and the number of structures that includes buildings, roadways and railways. As far as an atmospheric boundary is concerned, this approach tends to help in extracting real-time data for any atmospheric scale to estimate in-use material stocks. Besides, Google Earth gives access to historical images enabling us to do material flow estimations using spatial analysis as well. Moreover, it has advanced features to import or export GIS data as well.

## **1.6. Objectives of the Research**

The overall objective of this research is to develop a new model to extract material stock data using geographic imagery as a complementary method for MFA. This new model will be helpful in addressing data deficiencies in MFA. Further, the aim is to apply the newly

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developed model on French Railway Infrastructure to estimate the material stock of steel, concrete, cement, sand, and gravel by employing a bottom-up approach using their respective material intensities. Lastly, the objective is to recommend the prospects of applying this approach to other areas and to help make this method easy and efficient.

There are four specific research objectives under the overall objective. These specific research objectives were to:

1. Review the literature on urban infrastructure systems and Material Flow Analysis (MFA) studies on urban material flows and stocks;
2. Develop a Bottom-Up Material Flow Analysis Model using Secondary Method to address data limitations of MFA;
3. Apply this new model on French Railway System;
4. Estimate metallic and non-metallic material stocks in French Railway Infrastructure;

### 1.7. Outline of the Research Work

Table 1.2 gives an overview of how the different chapters of this research work have been designed and articulated with each other. It provides names of the chapters along with their brief description as well.

**Table 1.2. General outline of the research work**

<b>Title</b>	<b>Short Description</b>	<b>Pages</b>
Chapter 1 <b>Introduction</b>	Introduces the basic overview of this research work by describing Material Flow Analysis (MFA), its application and its shortcomings and presents <i>Google Earth</i> as a potential solution to overcome data limitations in MFA.	1-10

Chapter 2 <b>Literature Review</b>	Reviews the literature dedicated to the introduction and application of MFA in general context, data limitations related to MFA and past works using other secondary methods to address these limitations in order to set down the theoretical foundations of this research work.	11-35
Chapter 3 <b>Problem Statement</b>	Gives an overview of the problematic and related research question highlighting the particular points on which the research work is focused in order to bring a new methodology for addressing data limitations in MFA.	36-40
Chapter 4 <b>Methodology</b>	Describes and explains the methodology, data collection approach and main steps-by-step contents used to achieve the aimed objectives and to find the answers to the hypothesized research questions.	41-71
Chapter 5 <b>Input Data Interpretation and Discussion</b>	Explores the obtained input data in order to evaluate this new model approach for data extraction in order to estimate material stock.	72-112
Chapter 6 <b>Conclusions and Recommendations</b>	Summarizes all the scientific results of this research work as well as gives potential perspectives for future research works and related developments.	113-117
Chapter 7 <b>Extended Abstract (in French)</b>	Gives an extended overview of the research work in the French language including the main contents of Chapter 1 to Chapter 6.	118-145

## **CHAPTER 2**

# **LITERATURE REVIEW**

This chapter presents basic but sufficient background knowledge about the related terminologies, concepts, and literature, which is necessary to lay the foundation of the aimed research work. Initially, common definitions and understandings of the associated terms which are frequently used are given, followed by the introduction to infrastructure, various infrastructure types, and the concept of *Urban Metabolism* to provide a broad context of the topic and its relative positioning in the current literature. It further includes an introduction to Material Flow Analysis (MFA), its significance, the brief development history of MFA, its application in various fields, two main approaches employed in MFA and finally, a few MFA studies for stock estimation in building and transportation infrastructures.

The aim of providing such brief yet comprehensive detail about MFA is to enable all types of readers to completely understand MFA and its related concepts no matter whatever their respective backgrounds or expertise are. Once the essential background knowledge for MFA is established, then it ultimately reveals and discusses the data limitations in MFA, which other researchers have pointed out. It also explores how they employed different secondary methods and approaches to addressing those limitations and data deficiencies. It also explains various material stocks, their relative significance, types, and material intensities on railway infrastructure.



## **2.1. Related Terms**

### **2.1.1. Substance**

A single type of matter, which consists of uniform units, is called a substance. If these units are atoms, then this substance is called an element, and if these units are molecule, then this substance is called a compound (Atkins, 1992).

### **2.1.2. Goods**

Goods are substances or a mixture of the substances, which have a positive or negative value assigned from the market. Metals, coal, car are goods which have positive values while municipal waste is also a type of good, but it has a negative value. In economic terms, immaterial things like information and services are also goods; however, in MFA, only material goods are considered goods (Brunner, 2003; Lydie, 2019).

### **2.1.3. Material**

In daily usage, materials stand for both goods and substances. In MFA, it serves as an umbrella term for both goods and substances. Hence, wood (good) as well as carbon (substance), are taken as material in MFA (Brunner, 2003).

### **2.1.4. Flow**

Mass of the substance that flows per unit time is called flow. It can be defined as the mass flow rate (stan2web, 2019). The Flow into the system is called input while the flow out of the system is called output (Brunner, 2003).

### **2.1.5. Stock**

The amount of material stored in any process or system is called stock. It is actually a material reservoir within a system (stan2web, 2019; Brunner, 2003). These provide necessary personal

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and economic services within the infrastructure and are closely associated with extensive resource extraction, energy consumption and waste generation (Han, 2013).

### ***2.1.6. Anthroposphere***

The part of the Earth's atmosphere, which contains all human-driven processes, is called Anthroposphere. It is a human sphere of life, which is a complex system of energy, material, and information flows. Sometimes, it is referred to as techno-sphere. It can be seen as a living organism (Brunner, 2003; Jan, 2019).

## **2.2. Infrastructure**

### ***2.2.1. Definitions***

Although there is not any single agreed-upon definition for the term Infrastructure, there are some definitions, which are found in the literature.

American Society of Civil Engineers (ASCE) defines infrastructure as:

“The infrastructure supporting human activities includes complex and interrelated physical, social, ecological, economic, and technological systems such as transportation and energy production and distribution; water resources management; waste management; facilities supporting urban and rural communities; communications; sustainable resources development; and environmental protection.”

Infrastructure assets are physical structures, facilities, and networks that provide essential services to the public. These assets include transportation structures (roads, bridges, tunnels, railways, airports, and seaports), energy and utility companies, communication entities, and social services such as educational facilities and hospitals (Dawson, 2013).

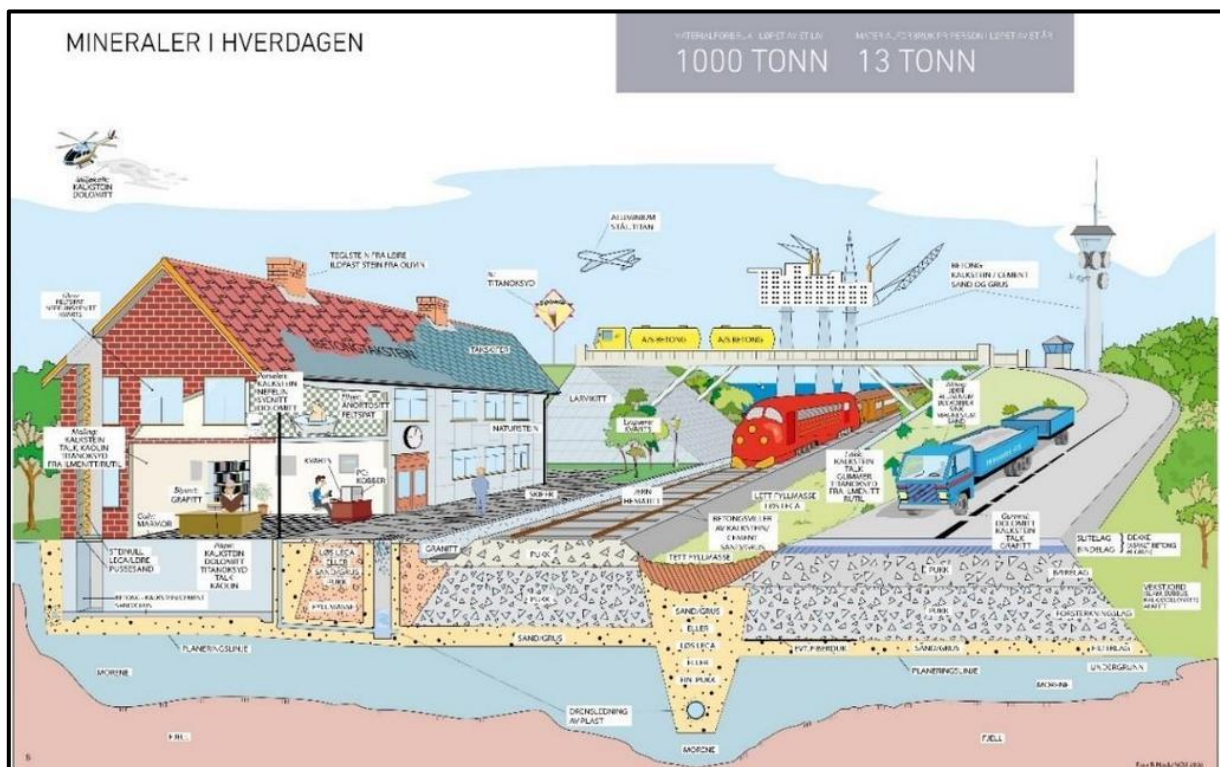
Infrastructure systems are the components of the society, attaching the essential commodities and services required to uphold or improve the standards of living. These components include

electric power, fuel, oil, gas, potable and wastewater, transportation, and communications (Fulmer, 2009).

### 2.2.2. Infrastructure Classification

In 1987, US National Research Council panel adopted the term "public works infrastructure" referring to highways, streets, roads, and bridges; mass transit; airports and airways; water supply and water resources; wastewater management; solid-waste treatment and disposal; electric power generation and transmission; telecommunications; and hazardous waste management (Council, 1987).

The American Society of Civil Engineers (ASCE) published an "Infrastructure Report Card", which presents the organizational opinion on the condition of various infrastructure every 2–4 years. As of 2017, they define 16 categories, which include aviation, bridges, dams, drinking water, energy, hazardous waste, inland waterways, levees, parks & recreation, ports, rail, roads, schools, solid waste, transit and wastewater (Engineers, 2017).



**Figure 2.1. The Urban Infrastructure and its components (Strategi, 2019)**

**2.2.3. *Urban Infrastructure***

Urban infrastructure, a broad classification of the infrastructure, is a versatile notion that exceeds a set of engineered systems, facilities, and utilities. It is also related to global and local governance systems, connected issues of economic growth, climate change, and municipal waste (Ferrer, 2018). It is a corresponding internal frame of a city as compared to the underlying structural support for the building. Modern populations and civilizations are becoming more dependent on urban infrastructure systems to provide essential services that support economic prosperity in growth and quality of life (Ouyang, 2012).

An urban infrastructure may include, as indicated from Figure 2.1, systems of urban physical structures that are under, on or above ground e.g. water supply and sewage systems, public transport systems, telephone and electric lines. During the nineteenth century, which can be regarded as the shaping period of the modern cities, modern structures such as new streets and boulevards, mass transit, new sewage systems, and the provision of gas, water, and electricity have also been included in essential elements of the urban infrastructure (Assefa, 2018; Infrastructure", 2019).

At the start of the twenty-first century, the concept of sustainable development was initiated and presented a new perspective to the world to address the issues related to economic development progress while protecting and preserving environmental systems and enhancing the quality of life for this and future generations. Recently, the element of sustainability has been added to the concept of urban infrastructure with the expectation of improved and more sustained urban development (Tiwari, 2016; Sahely, 2005).

**2.3. Urban Metabolism**

The rise of sustainable development has pushed us to see the urban infrastructures around us in a new manner in which we can relate it to a human body. A human body requires food as

input so that the body can convert this food into energy to run cellular processes within the body and to form building blocks such as proteins, lipids, and others. Similarly, the metabolic requirements of a city can be described as all of the energy and materials that the city and its inhabitants need to help them sustain and to keep the system of the city functioning and running correctly. Abel Wolman, in 1965, coined the term the *metabolism of the cities* in which he explained that metabolism of a city is analogous to that of a human body. He applied this concept to a hypothetical American city of one million inhabitants and estimated the flows of energy, water, materials, and wastes in and out of that city (Wolman, 1965; Kennedy, 2007).

Similar to the physical process in animals, trees, and forests, the Anthroposphere has its metabolism which includes uptake, transport and storage of all the substances, biochemical transformation within the Anthroposphere and quality and quantity of all off-products like gas, flue, waste, and sewage (Baccini, 1991).

Since the invention of this term, many researchers have applied this concept for the metabolism of organizations, infrastructures, regions, cities, and nations. The concept of urban metabolism saw formative work in the early 1970s, and it almost disappeared in the following years until in the last decade of the twentieth century when it re-emerged. Since then, this concept has gained popularity among researchers. There have been two parallel schools of thought of urban metabolism; one of them emphasizes energy equivalents while the other one focuses on mass fluxes of water and materials (Kennedy et al., 2011).

Although the motives for the application of the concept of Urban Metabolism are apparent; still, there does not exist any widely accepted method to apply this concept. Since long, mass-balance principles have been involved in diverse fields. In the early twentieth century, many researchers used the *law of conservation of matter* to balance system processes (Vidal, 1985). In the first half of the twentieth century, Leontief, a Russian-American economist, introduced input-output tables for the field of economics, which laid the base for wide-spread use of input-output methods (Leontief, 1977). In the following decades, a new tool and method,

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MFA, started to shape and emerge along with some other analysis tools such as pathway analysis, input-output method, Life Cycle Assessment (LCA) approach, Exergy, Cost-Benefit Analysis, Statistical Entropy Analysis, and Swiss Ecopoints (Brunner, 2003).

### **2.4. Material Flow Analysis (MFA)**

Material Flow Analysis (MFA) is a tool for systematic assessment of material flows and stocks for specific temporal and spatial boundaries within a predefined system. It is used to describe, evaluate, and investigate the metabolism of anthropogenic processes. The results of MFA can easily be controlled through a simple mass-balance equation governed by the *law of conservation of matter* in which all inputs, outputs, and stocks of a system are compared. It is a connection of the sources, their pathways and disposals, which refers to the throughput of the process chain that includes extraction, manufacturing, consumption, recycling, and finally, disposal of the materials (Bringezu, 2018; Brunner, 2003).

#### **2.4.1. Significance**

MFA provides a view of system analysis of different interconnected flows and processes to support the strategic and prioritized design of management measures. It is a must pre-requisite tool to operationalize the sustainability concept and to promote effective planning and natural resources management. Moreover, it is a powerful tool to support policy decision making in the fields of resource and environmental management. In terms of the policy, MFA can be used for early recognition, priority setting, to analyze and improve the effectiveness of measures and to design efficient material management strategies given sustainability (Bringezu, 2018; Barrett, 2002; Hendriks, 2000).

#### **2.4.2. Historical Development of MFA**

Around the 1980s, MFA became a very commonly used tool in the fields of waste and wastewater treatment, agricultural management, process control, resource conservation, life cycle assessment (LCA), etc. A group of researchers of the Centre of Environmental Science,

Leiden University, the Netherlands prepared several reports using MFA for flows and stocks of Cadmium, Chlorine, heavy metals, and other nutrients in the European environment (Kleijn, 1994; Voet, 1994). In the same period, a study to assess the flow of pollutants in the Rhine River was successfully conducted using MFA (Stigliani, 1993). By 2000, many studies had already been conducted using MFA in a multitude of fields in Austria, Germany, the Netherlands, Japan, and the US (Matthews, 2000).

### ***2.4.3. Application of MFA in Various Fields***

Since its development, MFA has been widely applied in different fields. In Environmental Engineering and Management, it has been employed in environmental impact statements, remediation of hazardous waste sites, design of air pollution control strategies, nutrient management in watersheds, planning of soil-monitoring programs, and sewage-sludge management. All of these tasks require a thorough understanding of the flows and stocks of materials within the Anthroposphere. It has a tremendous scope and application in the fields of industrial ecology, waste management, and resource management as well (Brunner, 2003).

### ***2.4.4. Objectives of MFA***

There are numerous objectives for conducting MFA. Some of them are listed below:

- a) **Performance evaluation:** Evaluation and assessment of the system performance to get material distribution information.
- b) **System Analysis:** Description of a system for further evaluation for flow and stock quantification.
- c) **System Comparison:** Comparison of different systems or technologies.
- d) **Early Recognition:** Early recognition of beneficial or harmful changes of flows and stocks.
- e) **Scenario Analysis:** Evaluation and optimization of the system.
- f) **Decision Making:** Reduction of the complexity of the system as far as possible still guaranteeing the basis for sound decision-making (Brunner, 2003; Allesch, 2015).

### **2.4.5. MFA Approaches**

There are static and dynamic MFA models. The static model aims at material flow analysis within a system boundary for a short temporal range, usually one year or so. MFA studies using this model have been conducted on a national, regional, and global scale for copper, silver, steel, and chromium since the 1990s (Graedel, 2004; Johnson J. J., 2005; Johnson J. S., 2006; Wang, 2007). While, the purpose of a dynamic model is to see the change in the material flows over time using time-series input data of the materials (Spatari, 2005; Takahiro, 2009). The dynamic model has been used since the 2000s, and a study on lead in Europe and studies on copper and steel have been conducted in North America (Elshkaki, 2004; Müller, 2011).

Mostly, there are two methods used for material stocks estimation for society; a) the top-down approach, and b) the bottom-up approach. The top-down approach is used to calculate material stocks by employing yearly time-series input statistical material data of production, economic input-output, and lifetime distributions of end-of-life products in society.

Besides, the bottom-up approach is applied when the top-down approach cannot be used due to the lack of data. In this approach, the number of products within specified system boundaries are quantified. After that, the material intensities of the products are multiplied by the number of products to estimate material stocks (Müller, 2006; Takahiro, 2009).

Top-down approaches have been used to estimate historic in-use stocks of copper in the US, North America, and Switzerland, timber in Switzerland, and minerals in the Netherlands (Müller, 2004; Müller, 2006; Zeltner, 1999). Similarly, few studies related to the estimation of steel and nickel in the US and Iron and steel in Japan were conducted by using bottom-up approaches (Drakonakis, 2007; Rostkowski, 2007; Yoshimoto, 1985).

### **2.4.6. MFA Studies**



Many studies have already been conducted to determine the flows of various materials, e.g. copper, silver, chromium, iron, steel, lead, steel, nickel, aluminium, cement, bitumen, wood, lime, glass, bricks, plastic, aggregates, and concrete in the US, Europe, and Japan (Kazue, 2009). A typical MFA study usually focuses on a snapshot of all of the flows of a particular material in a specific region for a set period, typically one year (Daigo, 2009). Following is a brief mention of a few studies in spatial, temporal, material, and infrastructural context to grasp a good understanding of scope and range of MFA.

#### **2.4.6.1. Spatial Context**

Emmenegger et al. (2003) conducted a study on urban metabolism in which they applied the bottom-up static flow analysis approach on a city level. They estimated the present stock of canton of Geneva in Switzerland for various metals and non-metals. Bergsdal, et al. (2007), Sartori, et al. (2008), Brattebø, et al, (2009), and Sandberg, et al, (2014) applied MFA on a national level to predict and compare future stock inputs and outputs. Kapur (2008) also used the same approach on a national scale for estimating the present stock of cement in the US for buildings, road, and water networks.

#### **2.4.6.2. Temporal Context**

Muller (2006) used the time period of a century to analyze the likely trends in the evolution of flows whereas Sandberg et al. (2014) considered a narrower time period of fifty years to limit uncertainties. By comparison, Deilmann (2009) and Serrand, et al. (2013) adopted twenty years time frame (Vincent, 2017).

#### **2.4.6.3. Material Context**

Gordon, et al. (2005), Lichtensteiger (2006), Zeltner, et al. (1999), Emmenegger, et al. (2003), and Schiller (2007) estimated material stocks of metals such as copper, iron, and steel for the US, Switzerland, and Germany. As far as non-metals are concerned, Kapur (2008), Tanikawa et al. (2015), Fishman et al. (2015), Shi et al. (2012) and Huang et al. (2013) have estimated

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material stocks of cement, aggregate, lime, glass, bricks, bitumen, and wood through MFA approach.

### **2.4.6.4. Infrastructural Context**

Lichtensteiger (2008), Muller (2006), Hu, et al. (2010) and Huang, et al. (2013) focused on building infrastructure, while Shi, et al. (2012), Schiller (2007), Kapur et al. (2008), Deilmann (2009), and Wiedenhofer et al. (2015) considered road, rails and water networks.

## **2.5. Selected Studies**

A semi-systematic qualitative approach has been used to conduct this research work by selecting literature that presents existing theoretical perspective related to MFA. It further helps in detecting common issues related to MFA data acquisition. Initially, a broadened review of scientific studies was conducted for understanding the basic concept of material flows and stocks. The review process was then narrowed down by considering scientific studies specific to material flows and stocks in urban infrastructure. Finally, the main focus for selection of the research literature was the relevance of the literature with the use of secondary methods for the acquisition of data in order to resolve data issues in MFA. The principle concern was the literature related to issues in MFA and data acquisition and the application of the secondary methods to address them. At last, material intensities related only to Railway Infrastructure have been summarized in order to incorporate the case study of French Railway Infrastructure.

## **2.6. Data issues in MFA**

### ***2.6.1. Data Deficiencies on Regional Level***

MFA is such a tool, that helps decision and policymakers to understand the process of urban metabolism for different spatial ranges. Since it allows regional activities and processes like construction, transportation, consumption, and disposal to be systematically linked with inputs and outputs of urban systems, thus, it has a great potential to be applied as a guiding

tool on a regional level (Hendriks, 2000). Bottom-up and top-down material flow approaches have been applied in numerous studies to attain satisfactory results. In a top-down approach, the historical consumption of materials in various infrastructures and their corresponding lifetime is used to estimate the material stocks. However, this approach is practically limited to a national or global scale due to data gaps and lacks a spatial resolution. This problem arises due to the lack of trade data or consumption data on the regional level. Thus, the estimation of stocks can also be a challenge for products with a long lifetime, like buildings and infrastructure. This estimation can be performed by a bottom-up approach in which all the relevant goods in a spatial boundary (like a city or region) and their corresponding material intensities are quantified and then aggregated. However, these approaches require a lot of labour and depend highly on statistical data. Also, very few case studies are available for cities and countries. (Bailang, 2018). There is a need for reconstruction of MFA data for various spatial ranges, including a regional scale, Still one of the obstacles preventing in building such data at different geographical scales proves to be costly both in time and effort (Courtonne, 2015). It is because that the regional data that are somehow available are typically unstructured, cross-disciplinary, different in formats and qualities, and come from heterogeneous sources. These sources may include official trade tables, scientific measurements, models, industries, or associations. This leads towards the implication that the databases of regional MFAs are usually highly heterogenic. On the other hand, sometimes, MFA data are not based on empirically well-founded data sets, but on an individual, isolated values, which are not always provided inconsistent formats. The available information basis is often considerably limited (Schwab et al., 2017).

According to Tachibana (2008), MFA is a vital tool to have a clear look at the structure of regional society and obtain indicators of the environment. Usually, regional communities are related to local governments. Therefore, the role of information in policymaking for local governments has gained greater importance. However, the role of MFA has not propagated that much to the local government scale due to lack of local statistical data, and the MFA methodologies for calculations of environmental indicators at the regional level have not yet

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been established. Generally speaking, studies on environmental indicators are directed on the national scale, and unfortunately, very few studies have been conducted at the regional level.

### ***2.6.2. Lack of Data Availability for Developing and Under-Developed Countries***

Data that support MFA studies are mostly available for developed countries. European Union (EU) and other developed countries have documented a sufficient level of data for conducting MFA and have already integrated MFA as a core component of environmental accounting to provide evidence-based policy and decision making (Vilaysouk et al. 2017). For example, the Sound Material Cycle Society in Japan applied three indicators for reaching social high-level policy objectives, which are derived from MFA. European Commission developed Resource Efficiency Scoreboard to track advancement towards increased resource efficiency in the member states. G7 countries devised a new initiative to integrate resource management and economic policy in one framework.

On the contrary, in developing countries where public data statistics are not well organized or less frequently available, data related to in-use stock is very difficult to find (Kazue, 2009). Developing countries like China, Russia, and India have an extensive stock of steel they lack in statistical data availability (Feng-Chi, 2011). Although implementation and monitoring progress of Sustainable Development Goals (SDGs), addressing resource productivity, management, and efficiency are mentioned as critical needs for the developing countries to ensure timely and affordable natural resource provision. However, Baninla et al. (2018) argue that mineral productivity is low in Africa and Asian developing countries compared to developed nations.

As opposed to critical information needs, developing countries also lack institutional capacity, financial resources, and human capital for statistic reporting. On the one hand, developing countries need information collection techniques suitable for their limited capacity and resources; on the other hand, monitoring and documentation systems need to be put in place.

For example, many studies applied to international databases. Still, those seem not entirely relevant to socio-economic characteristics of developing countries such as informal economic activities, different industrial systems, and underreporting trend (Vilaysouk et al. 2017).

### ***2.6.3. Data Uncertainties in MFA***

Data uncertainties in MFA, like in other environmental system analysis tool, such as LCA, is very often of varying standard. A few studies show that much of the data used in MFA studies are of low quality and high uncertainty. Given the intentions to use MFA in environmental accounting, and particularly as a tool for environmental policy and management, it is evident that data of lesser uncertainty has to be collected (Danius, 2001). The knowledge of the accuracy of data on the fact that certain data sets are reliable and representative enable users of the calculated results to assess the results' reliability and representativeness. One of the most important aspects of MFA is to make sure that uncertainties are kept to a minimum, but concerning results, it must be noted that uncertainties are inherent to MFA. Moreover, available statistical data sets do not sufficiently meet the specified data requirements in terms of completeness and level of differentiation. For the sake of analysis, thus, missing data must be generated through a combination of multiple sources, estimates, experts' opinions, and models which leads to a certain degree of uncertainty in MFA data (Schiller, 2017).

Schwab et al. (2017) have argued that in MFA studies, available information is critical for validity and can vary study to study depending on the material type and scope of the study. But it should also be kept in consideration that MFA studies with precise spatial and temporal system boundaries have data uncertainties due to limited knowledge. This uncertainty arises because, for every particular flow, there is only one correct value, which is most probably not known with absolute certainty. Thus, the results of MFA studies are closely linked to the quality of the data applied, which refers to the perceived degree of credibility of the given data. In a study by Laner (2015) on MFA input data uncertainty for plastic flows in Austria, they argued that material flows are specific for a certain geographical region, time frame, and the material. For this reason, there exists a certain degree of lack of information about MFA

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data input irrespective of the level of sophistication is adopted in the approach. The appropriate data for the actual system being studied may often not be available. Hence, data corresponding to the proposed system is derived from up- and downscaling using the transformation of data reported for other similar systems, or using expert judgment.

### ***2.6.4. Issues Related to Input Data Collection***

Patricio (2015) shows how to input data collection affects MFA results. Using time-series MFA data for 1996-2011 on three spatial levels, i.e. national (Sweden); regional (Stockholm region) and metropolitan (Stockholm, Gothenburg, and Malmo), it was depicted that how the quality of input data and errors in input data affect the overall results. They concluded that as the spatial level is decreased from national to regional and metropolitan levels, the data availability lowers as well.

Data acquisition for conducting MFA is complicated and thus is expanded to include informal sources, including market research, expert judgment, best scenarios, and other ‘hands-on’ knowledge (Rahman and Kim, 2019). Furthermore, beyond national and international statistical databases, secondary and complementary data collection techniques are also used in different studies recently (Bailang et al. 2018).

### **2.7. Use of Secondary Methods to Complement Data Issues in MFA**

Some secondary methods and tools, along with MFA, are required to be employed for better estimation and understanding of stocks and flows in order to overcome data issues that arise due to less or no availability of compiled statistical data at various spatial scales (national, regional or global), uncertainties in MFA data and lack of available data for developing and under-developed countries. A few studies have been conducted in which secondary methods such as Satellite Imagery Programs, Geographic Information System (GIS), Nighttime Light, and Remote Sensing have been employed to address the data deficiency in estimating stocks

and flows. In the following sections, these methods have been described briefly, and a few studies have been presented which employed these methods to address deficiencies in MFA.

### ***2.7.1. Geographical Information System (GIS)***

A Geographic Information System (GIS) is such a system that is designed to capture, store, manipulate, analyze, manage, and present geographic and spatial data. It refers to various technologies, processes, techniques, and methods, which are related to different operations and have many applications in engineering, planning, management, logistics, insurance, telecommunications, and business. GIS applications are tools that allow users to analyze space-related information, map data editions, and presentation of the results of all such operations (Clarke, 1986; Maliene, 2011).

Tanikawa and Hashimoto (2009) pointed out that the application of top-down and bottom-up MFA approaches using spatial and temporal data to estimate material stock has long been used. Still, such studies are not only insufficient for local policymaking on a regional level but also for geographical localization of the stocks. The assessment of urban metabolism in urban infrastructure is necessary to understand the changes in the material stock accumulation concerning spatial and temporal boundaries. It is because an enormous amount of construction material is required for the development of such infrastructure, and this signifies a new waste flow shortly. They argued that national and regional level estimates of material flows and stocks based upon available statistical data are helpful in assessing material input, output and stock accumulation over a time period but are unable to give their respective spatial distribution to the policy-makers. To achieve that, they proposed a 4-dimensional Geographical Information System (4d-GIS) bottom-up model in which they merged old available urban planning GIS maps of Japan with the latest digitized maps which they prepared for parts of the two target cities. This model enabled them to obtain additional information such as a number of floors, usage of buildings, road widths, and ground or surface information. They applied this model to the small areas of 8 km<sup>2</sup> and 11 km<sup>2</sup> areas of

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Manchester, UK, and Wakayama, Japan, respectively to determine material stocks in buildings, roadways, and railways along with their spatial distribution.

Fritz (2016) extended this approach to the whole city level, and they applied a similar model to the city of Vienna, Austria, using statistical data along with GIS data from various municipal authorities to estimate material stock in building infrastructures. In their research, they pointed out towards lack of detailed localization of the material stocks while considering statistical data only. The use of GIS takes care of this deficiency. Previous studies that used GIS in combination with statistical data had problems in combining different GIS data sets (e.g., combining a spatial data set with temporal data set). They proposed a better approach to merge different GIS data sets concerning building structure types and material stocks. There exist a lot of uncertainties in the approach due to the collection of data during an investigation, lack of documents, limited literature, outdated construction plans, and demolished buildings.

Tanikawa et al. (2015) further proposed a bottom-up model to estimate the in-use construction material stock in urban infrastructure for 47 prefectures of Japan using GIS. The scope of this study includes buildings, roads, railways, underground water networks, airports, seaports, and dams. Based on the structure type, different calculation methods and data sources were used. For buildings, two kinds of data sets were used for two different temporal ranges. One of them was GIS data set compiled by Japan's commercial map publisher and the other one was created using floor-space statistical data from the Ministry of Land, Infrastructure, Transport, and Tourism. For roads, country-wide GIS data and prefecture-level statistical data were used to obtain road classification, road lengths, and widths. While for railway only GIS data was considered, on the other hand, for underground pipe networks, only prefecture statistical data was available. The data sets for other structures were similar to the railway data. Finally, for all of the structures, material intensities were multiplied with several products for each structure type, as a norm in a bottom-up approach, to estimate material stock.



Meinel et al. (2009) conducted a study on the establishment of a database on building infrastructure in Germany using building data obtained from topographic maps, digital maps, and statistical data and then its implementation in a GIS environment to address data information deficit. The model is intended to be used as a nation-wide monitoring system of settlement and open space development.

Marcellus et al. (2012) employed GIS to make a record of construction material stocks and flows for building infrastructure in Philadelphia, Pennsylvania in the US, to encourage material recycling. Marcellus-Zamora et al. (2016) conducted a GIS-based study for the same region to characterize buildings described by land-use type.

Gruen et al. (2009) described plans of how a three-dimensional building and city models can be generated from figurative and semantic sources and how they can be integrated into GIS systems.

All of the studies, which have been mentioned above, and many others found in the literature, are mostly dealing with the flow and stock estimation of building infrastructure systems. There is hardly any study that takes into account the urban infrastructure as a whole or specifically deals with the transportation infrastructure. Another common aspect is that all of them, with the exception for a few, is an attempt to develop the data set, which could fill the gaps in already existing data. This process is very cumbersome, and a lot of assumptions had to be made for the sake of simplification. As far as the utility of the GIS data is concerned, according to Tanikawa et al. (2015), it helps improve MFA methodology, but, like MFA, its availability is the primary concern. It is beneficial for developed countries like Japan, where it is very randomly available. Still, for other nations, where there is little to no GIS data, the problem of data deficiency persists.

### ***2.7.2. Nighttime Light (NTL) Satellite Imagery***

Nighttime Light (NTL) Satellite Imagery is the Global satellite-observed nighttime lights product which has emerged as one of the widely used geospatial data collection tool. These

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products show the locations where artificial lighting is present and a measure of the brightness as observed from the space, as can be seen in Figure 2.2 (Elvidge, 2017). Since the late 1990s, Nighttime Lights satellite imagery has become an efficient tool to tie-in socio-economic parameters like urbanization, economic activity, and population. Recent researches exhibit that new and improved NTL imagery data can serve as a reliable means for dynamic analysis of these variables, whether they are increasing or decreasing with time. Especially, NTL imagery data becomes more relevant for detecting, estimating, and monitoring socioeconomic factors in countries and subnational regions where reliable official statistical data may be lacking (Bennett et al., 2017). Benefits of NTL imagery include the global coverage and the high spatial resolution with pixels corresponding to less than one square kilometer. Such high resolutions allow researchers to collect desired data at the global, national, and regional levels. Moreover, NTL imagery offers consistent quality all around the globe without any political manipulation (Bruederle, 2018).

In the domain of material stock estimation using MFA, Kazue et al. (2009) used nighttime light images as a helping tool to estimate in-use copper stock in developing countries of Asia, which include India, South Korea, Malaysia, Singapore, Taiwan, Thailand, Vietnam, and Sri Lanka. They argued that scarcity of available data and difficulty to estimate in-use stock material using bottom-up or top-down MFA approaches require the development of some novel method. They assumed that the presence of light reflects the use of electrically conducting materials, i.e. copper. Based upon that, they correlated the available statistical data of in-use copper data with light accumulation on Nighttime Light satellite images. They found the feasibility of their method, but still, their study lacked any validity of their approach.



**Figure 2.2. Nighttime light images have improved economic data collection in China (Goldstein, 2017)**

Using similar assumptions, Feng-Chi et al. (2011) applied the same technique for in-use steel stock for building infrastructures. They argued that unlike copper, steel is not an excellent conductive material; hence, just estimating it and correlating it to nighttime light will not yield good results. They hypothesized that radiance of nighttime light would be more in urban areas as compared to rural regions assuming that urban areas will have more coverage area as compared to areas and hence more radiance of nightlife and ultimately more steel in the buildings and infrastructures. They mentioned that steel stock in building infrastructure and nighttime light radiance might only be correlated in urban areas, while for rural areas, this is not that applicable.

Hattori et al. (2014) have concluded while using nighttime light for in-use steel estimation that there are uncertainties in their results and methodology, which need to be verified. Similarly, the collection of Nighttime light data is performed through satellite images gathered by sensors based upon their spatial resolution and quantization, which are and have been Improving with the time.

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Hanwei et al. (2017) conducted a study on regional and national level in Japan which was aimed at estimating in-use steel stocks for buildings and civil engineering structures using an enhanced new-generation nighttime light observation tool called Suomi National Polar-orbiting Partnership's Visible Infrared Imaging Radiometer Suite (S-NPP VIIRS) which compared stock estimations done through another version of NTL imagery tool, Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS). Sighting the deficiency of regional data collection while using traditional Top-down and Bottom-up approaches, they emphasized on the use of satellite imagery products like Nighttime light for its solution. They concluded that S-NPP VIIRS is far accurate than DMSP-OLS for building steel stocks and civil engineering steel stocks for the regional level. They put some light on limitations of this method; 1) the data is raw and lacks background noise (deviant pixels that do not represent actual color or exposure of the image screening, 2) these approaches are dependent on empirical relationships and correlations between nighttime light and in-use stocks.

It should be noted that all of the mentioned studies, along with others present in the literature, this approach heavily relies on nighttime light radiance in urban infrastructure. This radiance and its brightness are then correlated, using empirical relationships, to other factors, which are indicative of the urbanization, e.g. economic development, GDP, economic activity, business, or population, then this correlation is further utilized to estimate material stock.

### **2.8. Material Stocks in Urban Infrastructure**

Material stocks accumulated in the buildings and transportation networks within an urban infrastructure today are thought to be a potential partial substitute for primary resources through recycling and urban mining activities in developed countries (Brunner, 2011). MFA studies indicate that the overall material stocks within the economy of urban infrastructures are growing out of which significant share comes from construction minerals such as concrete, cement, sand and gravel, crushed stone, asphalt, and other aggregates (Hashimoto, 2007). Per capita, Material Stocks have been higher for the US, whereas material stock

growth rates have been highest in Japan for the last century. However, both Japan and the US have a very similar level of national Material Stocks, which ranges between 310 to 375 tons per capita, respectively (Fishman et al., 2014). In Germany, it is estimated that anthropogenic stocks grow at a rate of 550 million tons per year, whereas building infrastructure is responsible for around 85% of the material flow of all durable goods with life expectancy more than one year (Deilmann, 2018). Non-residential buildings in Germany account for approximately 6.8 billion tons of total material stocks, which is nearly half of the entire building stock (Ortlepp, 2016). Below is a brief overview of the various material stocks that are related to Urban Infrastructure.

### ***2.8.1. Metallic Stocks: Steel***

Until 2005, in-use steel stock estimates were available for only eight developed countries, i.e. the US, China, Japan, Austria, Australia, Canada, France, and the UK. Still, there exists a significant lack of certainty on the estimated amount of steel on a global scale. The methods used in most of the previous studies were based upon bottom-up and top-down approaches, which significantly displayed a lack of regional data estimates. Later on, steel stock estimation studies were also conducted for other developing countries where, over the last 20 years, the demand for steel increased multifold due to industrialization and urbanization. Table 2.1 illustrates per capita in-use steel stocks for 200 countries of the world where steel stocks have already reached or about to achieve at a saturation level (Stefan, 2013).

Scrap demand is expected to surpass primary steel by 2050, and the substantial demand would be generated from the developing countries as these countries remain far lower than the average saturation level, which is  $13\pm 2$  tons per capita (Pauliuk, 2013). For example, End-of-Life vessels are recycled in the developing countries (Bangladesh, Pakistan, and India) demonstrating high demand (average 50% national demand is met from vessel scrap) of the scraps in the construction sectors of these countries (Rahman and Kim, 2019; Rahman and Mayer, 2015).

**Table 2.1. Identified Saturation levels for mature steel stocks**

Sector	Steel Stock Saturation (ton/capita)
Construction Industry	10 ± 2
Machinery	1.3 ± 0.5
Appliances and others	0.6 ± 0.2
Transportation	1.5 ± 0.7
Total (rounded to near decimal)	13 ± 2

### ***2.8.2. Non-metallic Construction Material Stocks: Cement, Aggregate, Concrete***

Concrete is the most extensively consumed manufactured construction material for buildings, bridges, roads, and highways. It is one of the most crucial drivers of the material and energy flows within an urban infrastructure (ASCE, 2005). In a global context, there has been a rapid increase in modern concrete production. As of the first decade of the 21st century, it was reported to be approximately 12–15 gigatons (Gt) per year. In contrast, for the US, it has been reported to be in the range of 800-1,000 metric tons per year (Mt/year). (Van Oss, 2002; Van Oss, 2006). Ireland had a per capita concrete production rate of 8 metric tons as of 2007 (Woodward and Duffy, 2011). Traditionally, concrete consists of cement, sand, and crushed stones, of which around 15% consists of cement by weight.

In-use cement stocks in the US are estimated to be between 4.2 to 4.4 gigatons, which translates to 14.3 to 15.0 tons of in-use cement stock per person. It should be noted that the rate of growth has slowed in the last half-century, but the in-use cement stock per capita has doubled. More than 85% of the cement utilized in the previous century is still in use (Kapur et al., 2008). In China, residential buildings hold responsible for one-third of the total cement used, out of which more and more is being accumulated as unused stock. In contrast,

transportation infrastructure is expected to maintain its growth potential for cement use (Huang et al., 2018).

As of 2000, Cement and aggregate (sand and gravel) stocks in urban infrastructure for Switzerland were estimated to be 40 and 335 tons per capita (Lichtensteiger and Baccini, 2008). In Japan, from 1970 to 2000, stocks of non-metallic construction materials like sand, gravel, crushed stones, and aggregates have increased threefold (Hashimoto et al., 2009). As of 2000, crushed stones, sand, and gravel accounted for 75% of the 3,400 million metric tons of new materials entering the US urban infrastructure (Wagner, 2002).

## **2.9. Material Intensities and Estimation**

Metals like steel, copper, and aluminum, and non-metals like concrete and ceramics are used in bulk quantities in the construction industry. These construction materials are considered to consist of almost 40% of the Global resource flows annually (Schandl, 2017). During the twentieth century, such construction materials have been accumulated in the Anthroposphere as in-use physical stocks causing ample resource extraction and environmental impacts (Krausmann et al., 2017; Miatto et al., 2017; Miller et al., 2015).

Material stocks and flows quantification is a continuing challenge due to the fact that masses of construction materials are not consistently measured and recorded in statistics. Various methods are used for flows and stocks estimation. One of the methods is to use the number of product units e.g. No. of cars or monetary value as a substitute of the inventory of in-use materials and then multiplying it with a known ratio of material mass per unit of inventory (e.g. area or length) for material estimation. These ratios are called material intensity and are obtained in different ways (Heeren, 2019). Material intensity is a globally recognized measure of materials needed for the production, processing and disposal of a unit of a good or service (Turbide, 2020).

Material intensities can be obtained using on-site measurements, design documents, company data, governmental assessments, and construction codes and standards. Although, in reality, a

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combination of such approaches is required due to the scarcity of data (Kleemann, 2016; Marcellus-Zamora, 2016; Reyna, 2015; Mastrucci, 2017).

Material intensities vary for various infrastructure types. It should be noted that Railway infrastructure accounts for around 8% of motorised passenger movements and 10% of freight movement around the globe as compared to road network which accounts for almost 85% and 47% of passengers and freight movement respectively but railway infrastructure have higher material intensities compared to road networks (Transport, 2015). This is due to the fact that in railway infrastructure the smaller slope and larger curvature of the tracks produce larger earth movements and a larger change of landscape is required in railway infrastructure construction (Welfens, 2012).

In Railway Infrastructure, based upon traffic conditions, cost of the track, speed of movement, topography and several other reasons, different types of railway gauges are used. These gauges vary in mass per unit length e.g. narrow gauges are lighter than those of standard and broad gauges. Narrow gauges are cheaper to construct and require less right-of-way as compared to standard or broad gauges. On the other hand, narrow gauges have lower load-carrying capacity while standard or broad gauges tend to carry more load and heavy traffic. Based on these parameters, material intensity also varies for different tracks (Rail Gauges, 2020; Railways, 2020).

Material intensities are then further used in various estimation models for quantification of stocks and flows. Fundamentally, two methods are used for material stock estimation in a system; (1) Top-down approach, and (2) Bottom-up approach. In the top-down approach, material stocks are calculated by employing annual time-series statistical data for material production, economic input-output tables, and lifetime distributions of end-use products in a system. Contrarily, the bottom-up approach is used where the application of the top-down approach is restricted due to the lack of data. In this approach, the number of products within a specific system is quantified and then multiplied with the material intensities of the products to have an estimate of material stocks (Takahiro, 2009).



## CHAPTER 3

# PROBLEM STATEMENT

The literature review enabled us to understand that how the human-made Anthroposphere shaped up the modern urban infrastructures of the cities, and these urban infrastructures resemble a living organism having specific inputs, outputs, and stocks giving way to the concept of Urban Metabolism. The process of urban metabolism involves extraction, production, use, and disposal of natural resources that form the urban infrastructure. Since we have limited resources and our infrastructure is growing. Hence, we need to make policy decisions to achieve the goal of sustainability. Through the literature review, we learned that Material Flow Analysis (MFA) is one such a tool that allows us to make a material balance to make such decisions. We now understand that what are the data deficiencies in MFA and how different researchers have used secondary tools such as Geographical Information System (GIS) and Nighttime Light (NTL) Satellite Imagery Programs to address them. Chapter 3 discusses the over-all scope of this research work and reveals further research gaps which GIS and NTL are unable to solve. This research proposes the use of another Satellite Imagery Program called *Google Earth* for data extraction to eliminate data issues in MFA.

### **3.1. Global Scope and Research Interests**

It has been established through a review of the available literature that there are specific data issues in MFA. These issues are different and present a significant problem in conducting MFA studies on various spatial scales. Notably, lack of data on a regional scale poses many difficulties in performing material analysis and hence decision making on a regional scale. It has also been known until now that available statistical data is not well established for developing or under-developed countries. There also exists a significant degree of uncertainty in available input data. A considerable number of studies have opted to address these issues by employing some other data collection tools. The following section further explores the research gaps and data extraction deficiencies encountered by the researchers while using secondary methods in their MFA studies.

### **3.2. Research Gaps in Geographical Information System (GIS) and Nighttime Light (NTL) Satellite Imagery**

Geographical Information System (GIS) and Nighttime (NTL) Satellite Imagery have been applied as secondary methods along with MFA to solve data collection issues by various researchers in their respective studies (Hattori, 2014; Bailang, 2018; Tanikawa, 2009). They showed a significant level of success and displayed the potential and need for some external aids, which could help enhance data collection to solve the data-related issues in MFA. However, still, there are many research gaps, which those studies were unable to address.

NTL method is limited in its sector-specific application. For example, nighttime image, which works on the principle of the light radiance received by satellite from a defined target area, only takes into account the urban part of a geographic region. It does not take into account the material stocks present in the rural region due to the insignificant amount of radiance received by satellite. (Bennett, 2017).

Similarly, the NTL approach may take good care of steel or copper stock of building infrastructure in urban areas while failing to consider the steel stocks in the railway

## PROBLEM STATEMENT

infrastructure located in the rural zones. This failing is since usually building infrastructures are equipped with lighting facilities, and that signifies the presence of copper, whereas transportation infrastructure in general and railway infrastructure in specific not necessarily always equipped with lighting facilities, especially in far rural areas.

In addition, these methods are instrumental in determining economic growth, business activities, land occupancy, building infrastructure, and electricity consumption. However, this approach is only feasible for developed countries where the entire population and infrastructure system has energy and electricity facilities. Such methods are not suitable for developing or underdeveloped countries where energy or electricity is not available to the entire population and the whole infrastructure. This approach is also limited for the areas and regions where urbanization is not that well spread (Bennett, 2017; Goldstein, 2017).

Another issue related to NTL is that instead of direct observation or input data collection, these approaches heavily rely on empirical relationships or correlations, which involves several uncertainties. Once the NTL radiance is received, based upon this amount of radiance, it is then correlated to factors such as land occupancy, GDP, economic growth, building infrastructure type, electricity consumption, etc. Once that empirical relationship is established, then it is compared with other known material stocks to estimate material stocks of the target area.

On the other hand, GIS-based methods are helpful at coping the issues related to the sector-specific application but do not help in estimating the precise volume of the structures. These methods are able to take linear dimensions like lengths, widths, surface areas but they fail to take vertical measurements e.g. height of the structure or floor height. This limitation prevents such methods from volume estimation (Fritz, 2016).

GIS data at the national level can be obtained directly from national statistical bureaus in published form. However, at the regional and urban scale, there is limited data accessibility because data are generally dispersed among several organizations and firms and not found at

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one place. This deficiency makes it very tiring to produce a consistent set of data. The other issue is data availability because many data required are not available (Zhu, 2014).

As far as building infrastructure is concerned, there exists a significant amount of GIS data and maps, but for transportation infrastructure, GIS data is available for very few economies. This problem is even more severe in the case of lesser developed societies that lack geographical data collection.

### **3.3. Research Questions and Scientific Relevance**

It has been established until now that the role of MFA is very vital in material balance and stock accounting. It is also evident from a thorough review of the current literature on MFA that various data collection, availability, and uncertainty issues have been reported and encountered by the researchers in their research works. They have tried to address those issues with the help of secondary tools like GIS and NTL, but, still, there exist many research gaps while conducting MFA. As mentioned in Section 3.2, GIS and NTL have solved a few issues and have improved the data quality, but still, those methods are unable to compensate for the lack of regional data. They are also unable to fetch reliable data for rural parts of the infrastructure. The data collection problem is even severe in lesser developed economies. Moreover, the collection of data for transportation infrastructure (road network in general and railways in specific) is still a huge problem.

Therefore, it is fundamental to combine more comprehensive and readily accessible data collection methods that may improve the application of MFA in the developing countries as well as at a regional scale, and that may help assist in the extraction of missing data. In light of this discussion, we propose to use *Google Earth* as a solution to address limitations and uncertainties in data collection. It is feasible to obtain in-use material stock data in developed as well as developing countries at a city, regional, national, or global levels. As shown in Figure 3.1, with the help of a 3D street view, it is also capable of capturing all types of measurements, including length, width, height, and areas, which also enable us to calculate

volumes. This 3D view makes it possible to see the current situation of the target area. It can also allow us to estimate quantities of all type of infrastructures that includes building, roadways, and railways.



**Figure 3.1. An actual street view of The Colosseum, Rome (Paul, 2019)**

As far as an atmospheric boundary is concerned, this approach tends to help in extracting real-time data for any aerial scale to estimate in-use material stocks. Besides, Google Earth gives access to historical images enabling us to do material flow estimations using spatial analysis as well. Moreover, it also has advanced features to import or export GIS data, which will allow us to benefit any existing GIS map.

## **CHAPTER 4**

# **METHODOLOGY**

The utility of MFA and its application in material balance, material accounting, stock estimation, and policy decision making have been well discussed in the previous chapters. Data issues and limitations of MFA have also been pointed out by exploring already existing literature. Until now, the problem statement, research questions, and over-all scope of this research work have been established clearly. The main objective of this study is to develop a novel method for data extraction to address data issues faced while conducting MFA. Chapter 4 describes the detailed methodological framework adopted in this research work. It clearly defines the methodological framework of the research by describing and explaining target infrastructure, data sources, materials and structures in consideration, the scope of the research, and spatial and temporal boundaries, which help to develop the model for data extraction using Google Earth as a secondary approach. Subsequently, a complete data collection approach has been explained, and finally, the type of data that will be collected has been described. Then a detailed procedure of data extraction using Google Earth has been presented, followed by the material estimation method that is applied in this research work.

### 4.1. Methodological Framework

A framework of research is a structured description of the components of the work which are joined together methodologically. This section is dedicated to the overall structure of the methodology, which has been adopted in this research work. Figure 4.1 presents a complete methodological framework of this research work depicting all constituting components.

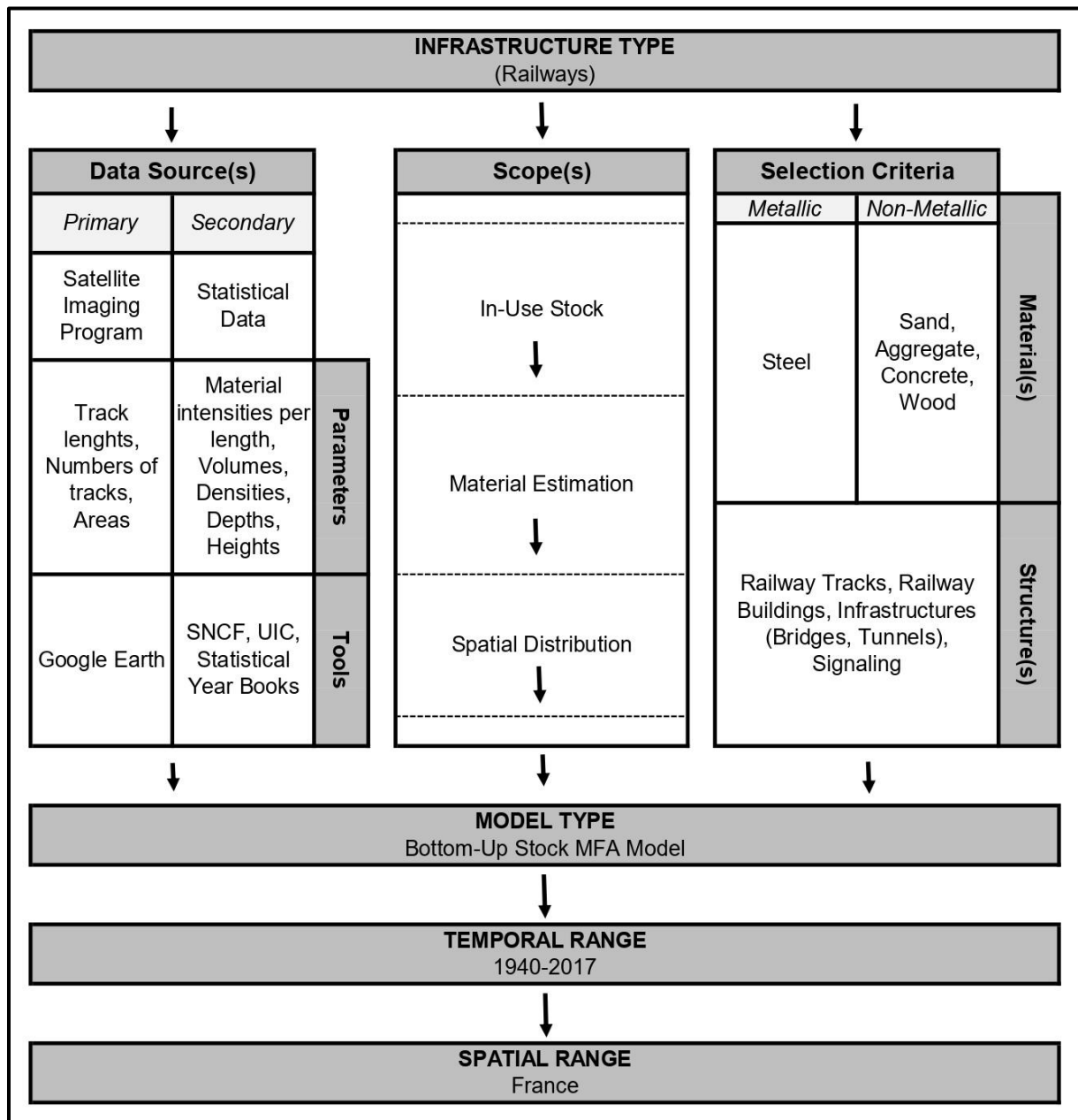


Figure 4.1. Methodological Framework of the present research work

### 4.1.1. *The Infrastructure: French Railway System*

Many studies have been carried out on urban infrastructure systems for determining stocks and flows present in the anthropogenic sphere. Although a handful of studies are present for transportation infrastructure, the majority of the MFA studies focus on building infrastructure. Within transportation infrastructures, the road infrastructure has been studied by numerous studies in the US and Europe (Wiedenhofer, 2015; Miatto, 2017). There have been very few studies that focused on railway infrastructure independently, even though it contributes a significant share in human-made secondary resources of material stocks. Hence, we addressed this issue and selected railway infrastructure for our research work.



**Figure 4.2. Extent and Spread of French Railway Network (SNCF, 2020)**

Given its well-maintained statistical data and fully developed infrastructure in modern Anthropocene, the French railway system was selected to carry out this research work and perform a case-study to validate our method of data extraction. French Railway Infrastructure is one of the oldest and largest in Europe and the World. Dating back to the 1820s, the French



Railway System was initialized by some private companies to haul coal for short distances (Dunham, 1941). Later on, the French government formed a partnership with these private companies until in 1938 the French Railway System was nationalized and came into the form in which it is today. Since then, it is managed by *Société Nationale des Chemins de fer Francais* (SNCF) (Dunham, 1955; Ribeill, 2006).

As of June 2017, the French railway network, under the administration of SNCF, has a commercially usable railway line network of more than 29,000 Kilometers. Almost half of the network, 15,141 km to be precise, is electrically operated. Around 1,876 km of the total lines are high-speed lines (LGV), and 16,445 km is double or multiple tracks lines. Although freight transport is in decline since the early 1980s, the French railway network has 819 km of lines for freight services (NETWORK, 2019). An extent and spread of the French railway network can be seen in Figure 4.2 (SNCFReseau, 2019).



**Figure 4.3. Single and Double Line Originating from A Railway Station**

There are approximately 470 railway tracks in French Railway Infrastructure, which have been given an identification number by SNCF. There are about 16 types of rail tracks in French Railway Infrastructure, which are listed in Table 4.1 along with the symbols, which

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we have allotted to them. Mainly these tracks are either electric lines or non-electric lines, which are further categorized based upon track use, i.e. a) *Mixed Line*, used for both passenger and freight services, and b) *Freight Lines*; used for freight services only. There are a few rail lines that cover suspended, proposed, non-operational, or tracks used by networks other than SNCF, which make a very negligible portion of the whole French Railway Infrastructure. Furthermore, based upon a multiplicity of the track, rail lines are of three types; a) Single line, b) Double line, and c) Multiple lines. A single line is such a railway line that runs as a single track for the whole length (origin to the destination point) whereas double and multiple lines run as two way and multiple ways, respectively (Figure 4.3).

**Table 4.1. Types of Rail Tracks in France with symbols allotted in our work**

Sr. No.	Track Type	Symbol	Sr. No.	Track Type	Symbol
1.	Double track High-Speed Lines (LGV)	L <sub>GV</sub>	9.	Freight Electric Lines, Double Track	F <sub>ED</sub>
2.	Mixed Electric Lines, Single Track	M <sub>ES</sub>	10.	Freight Electric Lines, Multiple Track	F <sub>EM</sub>
3.	Mixed Electric Lines, Double Track	M <sub>ED</sub>	11.	Freight Non-Electric Lines, Single Track	F <sub>NS</sub>
4.	Mixed Electric Lines, Multiple Track	M <sub>EM</sub>	12.	Freight Non-Electric Lines, Double Track	F <sub>ND</sub>
5.	Mixed Non-Electric Lines, Single Track	M <sub>NS</sub>	13.	Freight Non-Electric Lines, Multiple Track	F <sub>NM</sub>
6.	Mixed Non-Electric Lines, Double Track	M <sub>ND</sub>	14.	Non-operated Line	N <sub>O</sub>
7.	Mixed Non-Electric Lines, Multiple Track	M <sub>NM</sub>	15.	Suspended Line, Re-opening Envisaged	S
8.	Freight Electric Lines, Single Track	F <sub>ES</sub>	16.	Other Network or Tourist Operated, Electric	M

### 4.1.2. Materials & Structures

French railway systems consist of railway tracks, railway buildings, railway stations, bridges, culverts, tunnels, level crossings, signalling, and yards. Table 4.2 presents several such structures in the French railway system as per inventory maintained by the SNCF group (NETWORK, 2019). In this research work, railway tracks, railway signals, tunnels, bridges,

and railway stations have been selected as basic structures that will be considered for the data collection. Furthermore, French railway infrastructure is a rich stock resource of metallic and non-metallic materials. For material stock estimation purposes, metals, e.g. steel and non-metals such as concrete, sand, aggregate, and wood have been considered.

**Table 4.2. Inventory of Railway Related Structures in French Railway System**

<b>Sr. No.</b>	<b>Structure Type</b>	<b>Quantity</b>
1.	Level Crossings	17351
2.	Tunnels	1742
3.	Bridges	26733
4.	Signal Box	2273
5.	Railway Stations	3054
6.	Retaining Walls	19863
7.	Pedestrian Bridges	1204

#### **4.1.3. Data Sources**

This research work aims to construct a model that may help in addressing data extraction issues in MFA. This research work hence heavily relies on a secondary method, Google Earth, which we used to collect material stock data within the selected part of the French railway system. Along with Google Maps, SNCF inventory and maps have been used for the basic input data regarding the French railway network.

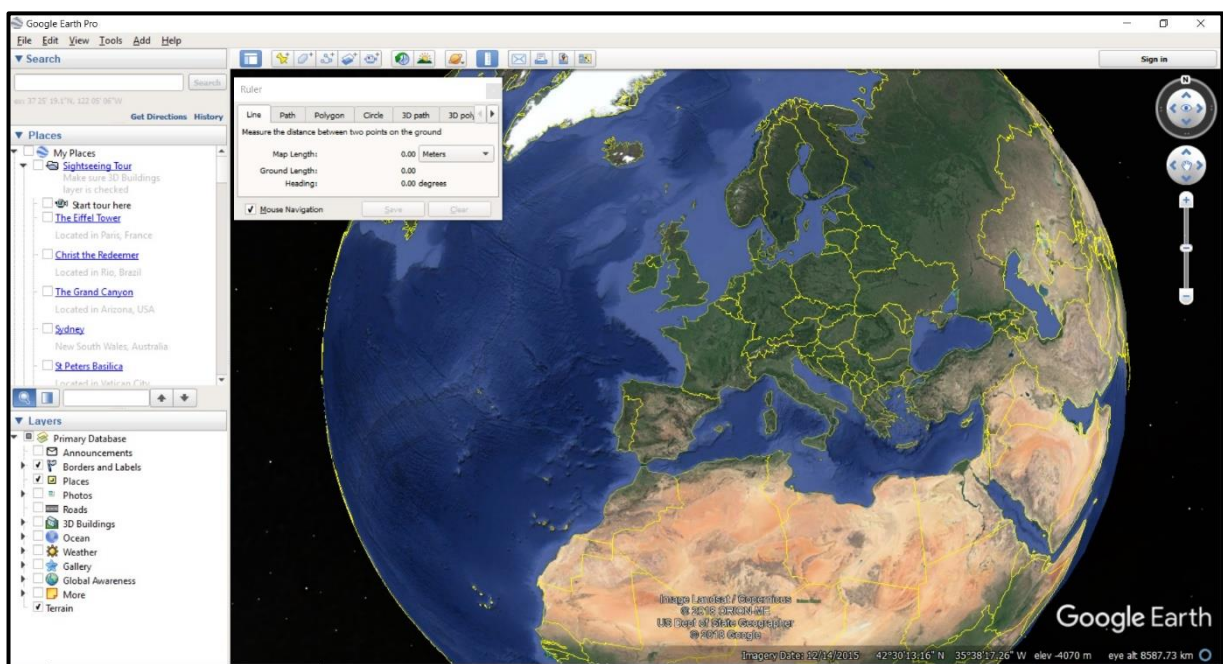
##### **4.1.3.1. Primary Data Source: Google Earth**

Google Earth is a unique mapping and tagging program that employs composite imagery to make a comprehensive and interactive map of the Earth by bringing together many satellite and aerial images. These maps can be combined with various overlays such as street names, weather patterns, crime statistics, commercial business locations, real-estate prices, population

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densities, and many others (Google Earth, 2019). The application is such a capable tool that allows people, at an individual or group level, to perform various activities such as tracking climate change, recording history, or grabbing street views (Davis, 2019). It presents the Earth as a three-dimensional globe. Google also refers to Google Earth as a geographic browser.

Google Earth is available over the internet in the free version which provides numerous features that are helpful for educational purposes. It is also available in more advanced and professional purchasable versions which offer additional capabilities such as higher resolution printing, movie making, and image saving (What is Google Earth?, 2019). Figure 4.4 shows a screenshot of the Google Earth being run on a Windows 10 platform, which is showing all of its prominent features, notably, layers pane, measurement dialogue box, zooming and rotating options, and places pane.



**Figure 4.4. Screenshot of Google Earth on Windows 10**

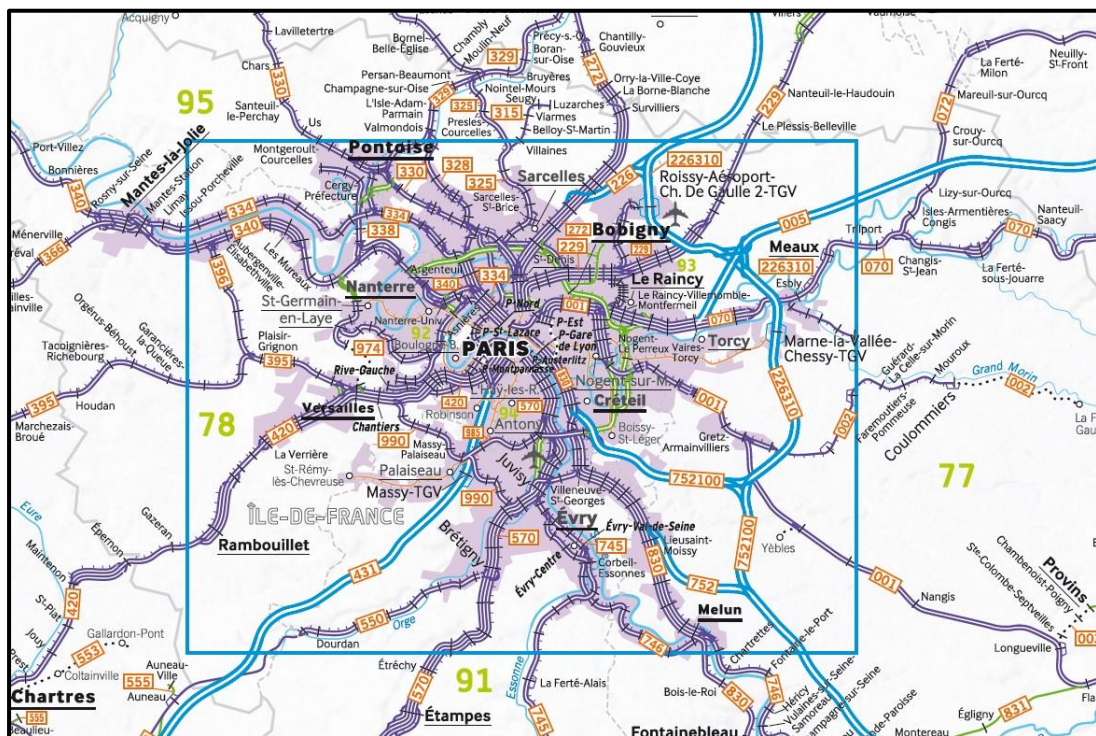
Through the help of search options and the abilities to pan (moving through the map), zoom, rotate, and tilt the view of the Earth map, Google Earth has been used to collect data for the French railway system. These data include lengths of the tracks, track type based upon



multiplicity (single, double or multiple), number of bridges, level crossings, tunnels with their respective lengths and number of railway stations. The detailed procedure of how this was achieved has been thoroughly described in the following sections of this chapter.

#### 4.1.3.2. Secondary Data Source

Multiple SNCF resources have been used to collect the primary input data on the over-all railway network of France. SNCF regularly updates its complete maps of the SNCF network spread inside and outside of France along with regional maps, which are based upon ongoing construction and maintenance works in respective regions of France. SNCF map, updated as of September 2017, has been used in this research work to gather information on the extent of the network. This map details out all the railway lines by explicitly distinguishing, using colors and symbols, various lines based upon their usage, track type, track multiplicity, and other features like planned, suspended, or under-construction lines. Figure 4.4 depicts only a portion of that map. The map is drawn at a scale of 1:1000000 (1 cm:1 km), which enables to



directly measure the lengths of the track.

**Figure 4.5. Screenshot of the part of the SNCF Network Map (SNCF, 2020)**

It can be seen in Figure 4.5 that all the relevant information including track types (in different colors), locations, SNCF identification number, origin and destination of a particular railway line, railway stations, and department numbers along with their boundaries are visible. As mentioned in Figure 4.1, all such data has been obtained through SNCF maps.

One of the objectives of this research work is a stock estimation of French railway infrastructure. For that purpose, material intensities were essential and have been taken from various other sources, which predominantly include available literature on railway infrastructure, International Union of Railways (UIC), and other railway-related organizations and codes.

**4.1.3.3. Temporal and Spatial Range**

The current French railway infrastructure, which started to obtain modernization around 1981, has been maintained and managed by the group SNCF since its foundation in 1938. All of the stock since then has been considered in this research work. In the spatial sense, the SNCF network is spread in mainland France along with its overseas departments. Only mainland France railway network has been considered in this research work, which is covered in 13 metropolitan regions of France on the European continent.

**4.2. Development of Method for Data Extraction from French Railway Infrastructure Using Google Earth**

Section 4.1, the methodological framework, detailed out French railway infrastructure system and spatial and temporal boundaries in consideration for this research work. All primary and secondary data sources and structures and materials in the discussion have also been explained. Now, complete detail of how the method of data extraction from French railway infrastructure was developed using Google Earth is given. The entire flow diagram in this regard is summarized in Figure 4.6.

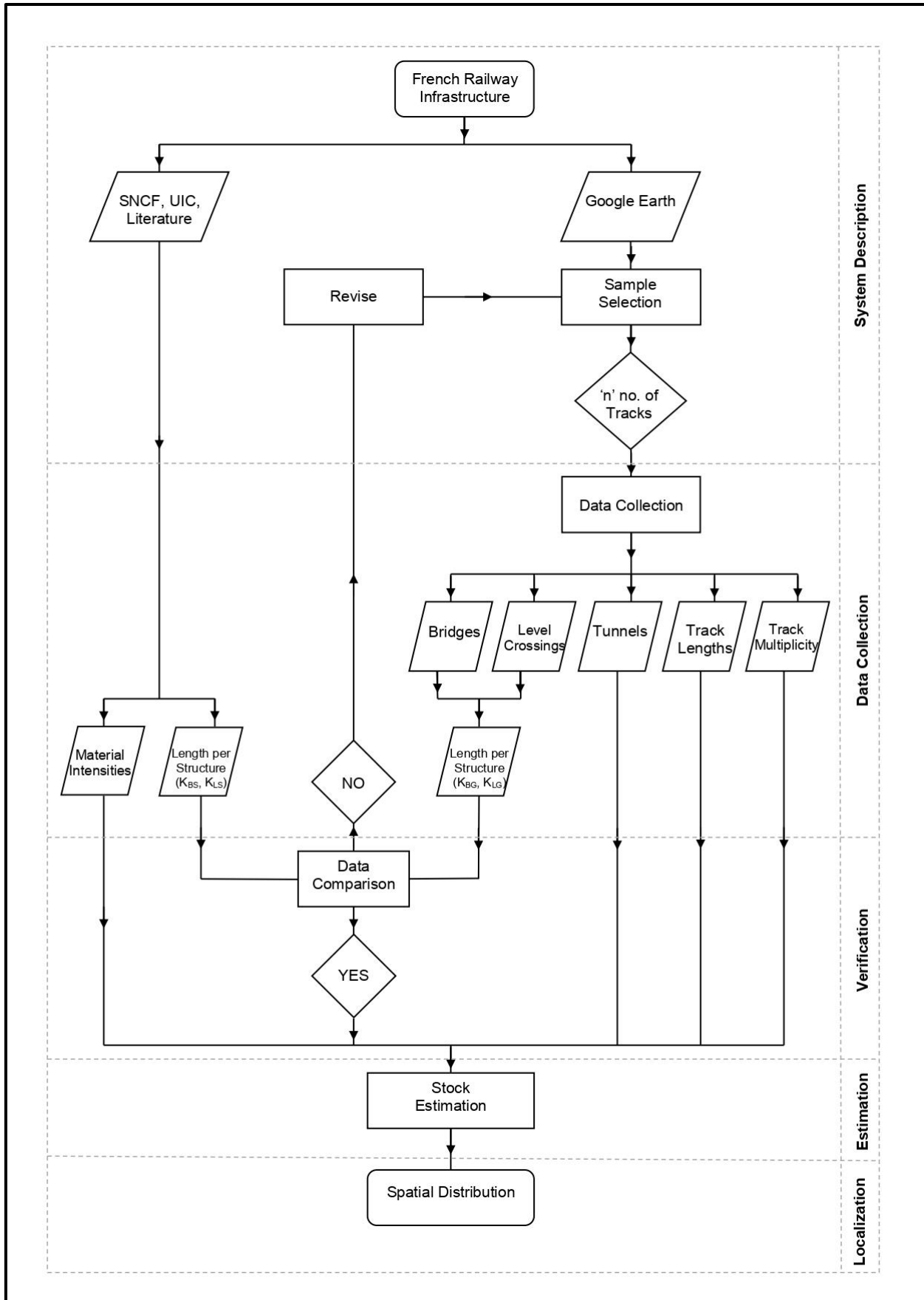


Figure 4.6. Flow Diagram of Development of Proposed Method

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In the flowchart, different types of shapes have been used to represent various entities. The rectangle shape represents the ‘process’, the rhombus shape represents the ‘decision’, while the parallelogram shape represents the ‘data inputs and outputs’. The arrows indicate the direction of these entities to understand the logical sequence. The flowchart is divided into 5 phases, i.e. System Description, Data Collection, Validation, Estimation, and Localization.

***System Description:*** This phase points out the general methodology and data sources that have been adopted for the development of the proposed method. French railway infrastructure is the selected system for the research work. Two types of data have been used as ‘input’ data; (a) Google Earth and, (b) SNCF maps, inventories, UIC datasheets, and available literature. The sample selection ‘process’ includes a selection of ‘n’ number of tracks for which the data will be collected later on. The criteria for sample selection are based upon the type of the track, its geographical location in France, and the respective lengths of the tracks. The complete sample selection criteria have been explained in Sections 4.3.

***Data Collection:*** This phase presents the structural entities for what the data will be collected. These entities include the length of the tracks along with their multiplicity, number of tunnels and their respective lengths, number of bridges, and number of level crossings. The selected sample from the previous phase is then subjected to data collection in terms of the above entities using Google Earth. In parallel, material intensities were also taken from the available literature to be used for material estimation in the later part of the research work.

***Verification:*** This phase signifies verification of the approach which has been proposed in this research work. Due to time stipulation of the research work and cumbersomeness and difficulty in the collection of manual data from Google Earth, the data extraction using Google Earth for the whole French railway infrastructure was impossible. French railway system, just like any railway infrastructure, is brimming with civil engineering structures such as bridges, tunnels, and level crossings throughout the lengths of railway tracks. Out of all these structures, bridges and level crossings are the most frequently repeated structures that intersect or cross the railway tracks. Based upon their frequent appearance along the paths of



the railway tracks, four comparable parameters were developed based upon Google Map and SNCF data for the sake of verification of the proposed method developed in this research work. These four parameters are;

- a) Kilometer per bridge for Google Earth Data ( $K_{BG}$ ),
- b) Kilometer per level crossing for Google Earth Data ( $K_{LG}$ ),
- c) Kilometer per bridge for SNCF Data ( $K_{BS}$ )
- d) Kilometer per level crossing for SNCF Data ( $K_{LS}$ )

In general, these parameters are simply the distances, after which each structure in consideration is repeated. These parameters were calculated using the following equations:

$$K_{BG} = \frac{\text{Total length of the tracks measured in Google Earth}}{\text{No. of bridges counted in Google Earth}} \dots \dots \dots (Eq. 1)$$

$$K_{LG} = \frac{\text{Total length of the tracks measured in Google Earth}}{\text{No. of level crossings counted in Google Earth}} \dots \dots \dots (Eq. 2)$$

$$K_{BS} = \frac{\text{Total length of the tracks in French Railway system as per SNCF}}{\text{No. of bridges in French Railway system as per SNCF system}} \dots \dots \dots (Eq. 3)$$

$$K_{LS} = \frac{\text{Total length of the tracks in French Railway system as per SNCF}}{\text{No. of level crossings in French Railway system as per SNCF}} \dots \dots \dots (Eq. 4)$$

The value of  $K_{BG}$  is to be compared with  $K_{BS}$ , while  $K_{LG}$  is to be compared with  $K_{LS}$  for validation purposes. The aim is to obtain a minimum percentage margin of difference between them. Using equation three and equation four and number of bridges and level crossings in the French railway system, given in Table 4.2, as per SNCF inventory, parameters  $K_{BS}$  and  $K_{LS}$  were calculated and are presented in Table 4.3.

**Table 4.3.  $K_{BS}$  &  $K_{LS}$  (Km/Bridge & Km/Crossing for SNCF Data Using Eq. 3 & Eq. 4)**

Parameter	Value
$K_{BS}$	1.08
$K_{LS}$	1.67

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Above are the single unique values obtained by using Eq. 3 and Eq. 4 which describe that, on average, there is a bridge after every 1.08 Km while there is a level crossing for every 1.67 Km of the French Railway System. The significance of these values is such that if the similar parameters ( $K_{BG}$  and  $K_{LG}$ ) obtained for the data collected using Google Earth have values comparable to  $K_{BS}$  and  $K_{LS}$ , then, the newly developed approach of data collection is validated.

*Estimation:* This phase deals with the material stock estimation in French railway infrastructure by considering several product data, i.e. track, bridge, tunnel, and level crossing data from the Google Earth and multiplying them with material intensities as taken from various sources.

### **4.3. Sample Track Selection Criteria in Google Earth for Data Extraction**

As explained earlier, it is not possible to collect data for the whole of French railway infrastructure in this research work while using Google Earth since it requires an extensive effort and extended time. Data for a portion of French railway infrastructure has been collected. This portion covers 9182.7 km (almost 32% of total length) of track lengths, which encompasses 95 tracks (nearly 20% of the total number of tracks).

It is very vital to any research method or model that the data be representative of the system into consideration. French railway infrastructure is very diverse and spread in the plains and the mountainous regions of France. Also, France has five overseas regions and some other collectives and territories (Geography and climate, 2019). Having representativeness of the data, criteria were developed to select the tracks for which data was extracted using Google Earth. Four criteria were developed to make this selection, which is described below:

### 4.3.1. Track Length

Although SNCF does not make any distinction among the railway tracks in terms of their lengths, for the sake of representativeness of all length ranges of tracks, the French railway system was divided into three categories. Class-A: long tracks (>300 km), Class-B: medium tracks (100-300 km), and Class-C: short tracks (<100 km). There are 7, 20, and 68 number of tracks belonging to Class-A, Class-B, and Class-C, respectively which were selected in this research work.

### 4.3.2. Track Electrification

As mentioned in Section 4.1, individual tracks are electrified, while others are not. The structure and system for both types of rail tracks may vary. To achieve representativeness, both track types have been selected. Out of all tracks that have been selected, 44 tracks are electrified while rest is non-electrified.

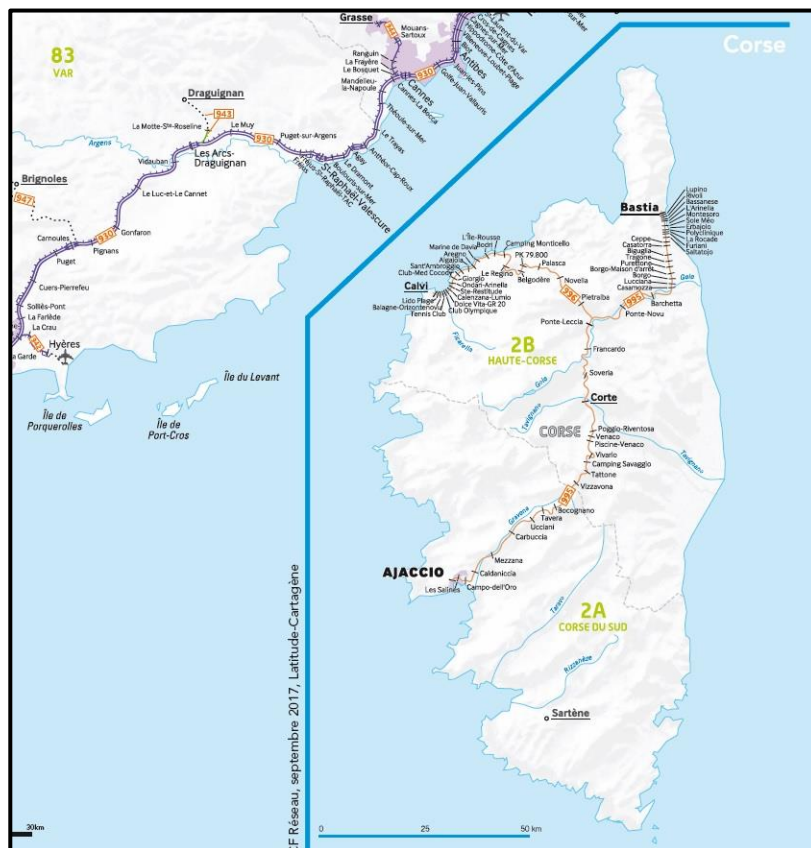


Figure 4.7. Region of Corsica in the European Continent (SNCF, 2020)

### **4.3.3. Track Usage**

There are two types of tracks concerning the provision of service and usage in French railway infrastructure; (a) Mixed Line, used for both passenger and freight services, and (b) Freight Lines, used for freight services only. Due to the difference in their usage and the geography, there might be a potential variance in the appearance of bridges and level crossings, which may affect the variables  $K_{BG}$ ,  $K_{LG}$ ,  $K_{BS}$ , and  $K_{LS}$ . To keep the difference, both types of lines were considered in the appropriate proportions. A total of 56 mixed lines while 39 freight lines were selected.

### **4.3.4. Track Geography**

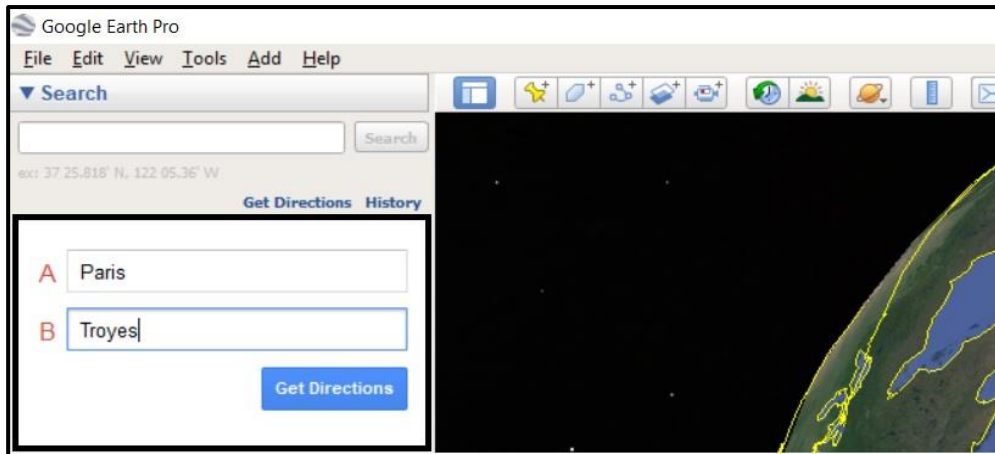
As explained earlier, the railway infrastructure in France is spread in the flat lands and the mountainous terrains all across France and the overseas regions and territories. Only the tracks in mainland metropolitan France in the European continent have been considered except for the one island region *Corsica* since it has very insignificant railway infrastructure, as seen in Figure 4.7, and is not managed by SNCF. All other overseas regions and territories have also been excluded for the reason.

## **4.4. Data Collection Procedure Using Google Earth**

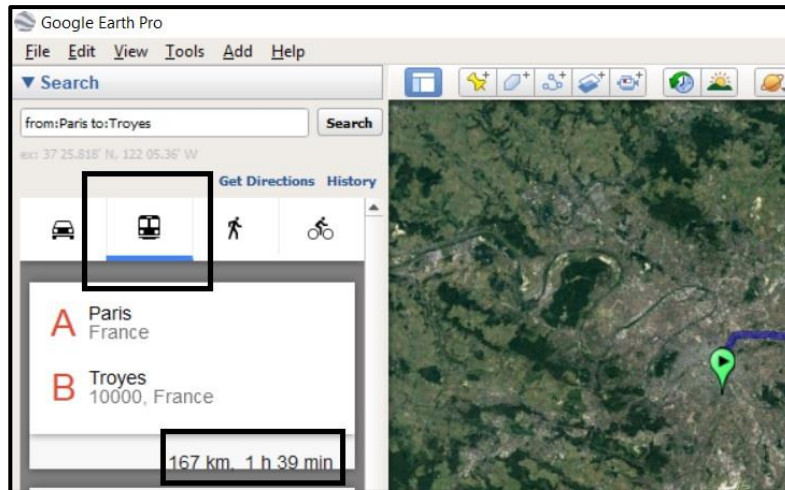
This section describes a thorough step-by-step procedure of data extraction that has been employed in this research using Google Earth.

### **4.4.1. Pinpointing the Track on Google Earth**

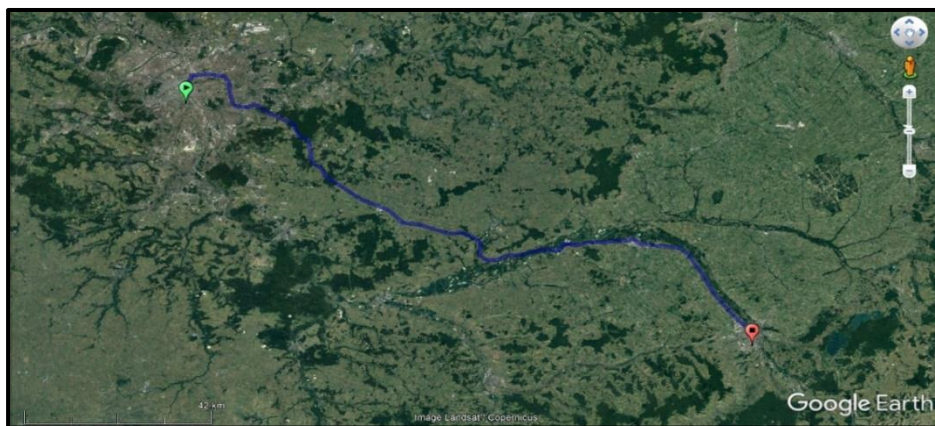
In the user interface of Google Earth, clicking the tab ‘*Get Directions*’, directs towards a new dialogue box pane, which lets the user enter two locations; A (origin) and B (destination), as shown in Figure 4.8. Inputting the origin and the destination of the selected track and clicking the railway route option (Figure 4.9) pinpoints it on the Google Map by highlighting its route and extreme positions through markers (Figure 4.10).



**Figure 4.8. Dialogue Box for Inputting Origin and Destination of Desired Track (Google Earth)**



**Figure 4.9. Selection of 'Railway Route' for Selected Track (Google Earth)**

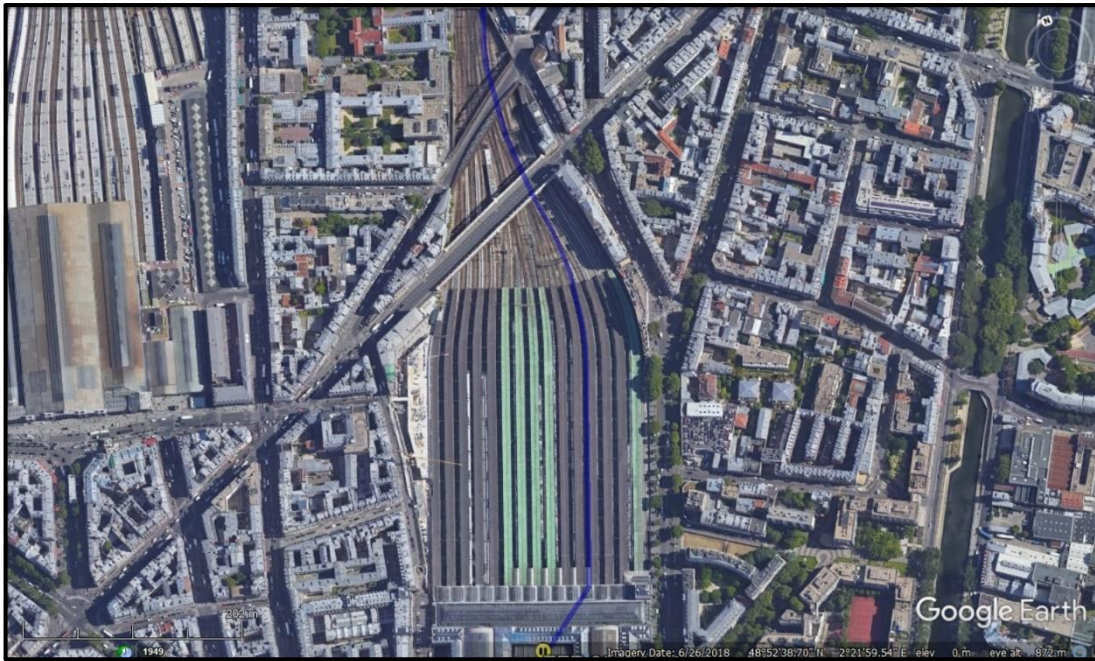


**4.10. Selected Route on Google Earth**

**Figure**

#### ***4.4.2. Getting Along the Selected Track***

Once the selected rail track has been pinpointed on the Google Earth Graphic User Interface (GUI), zooming in the frame towards the origin of the track decreases the altitude of the satellite view and unveils the components of the railway infrastructure and the actual start point of the track (Figure 4.11).

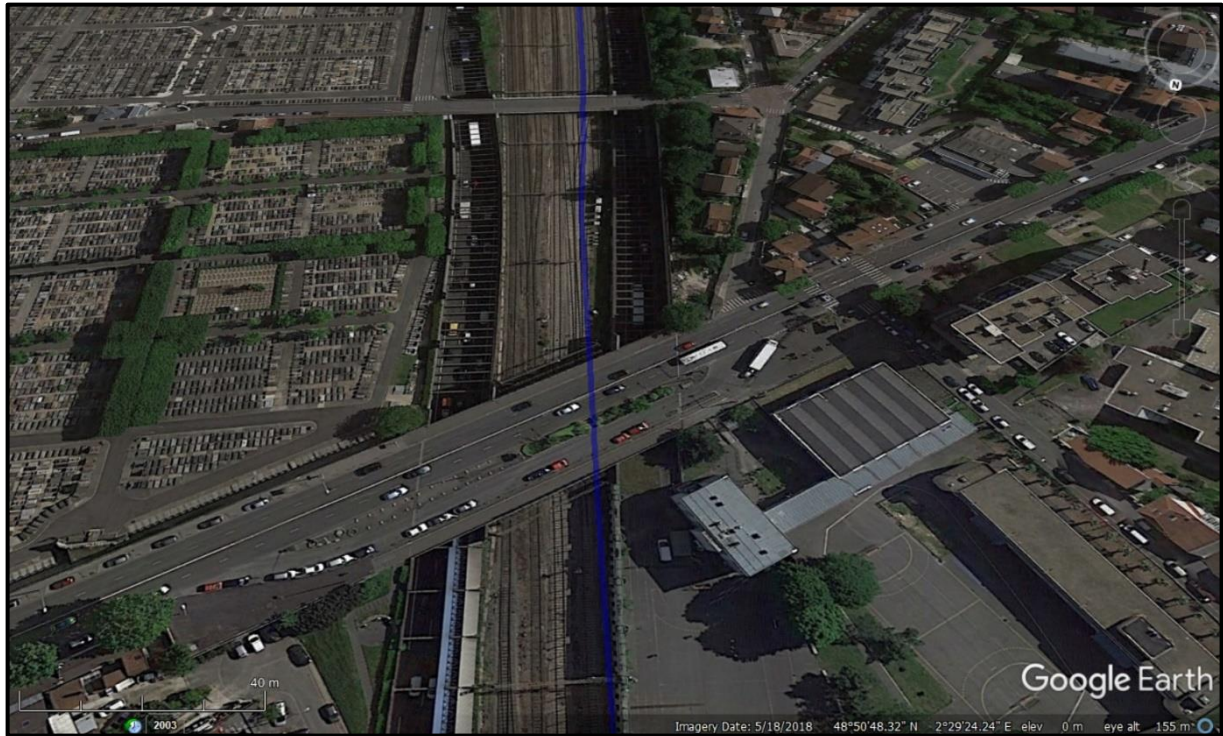


**Figure 4.11. Origin of the Selected Track showing Railway Tracks**

#### ***4.4.3. Travelling Through Selected Track for Data Collection***

Once the screen and GUI are set on the starting point of the origin in the selected track, pressing forward or backward tab on the keyboard enables the user to advance or retreat along with the track respectively. Similarly, the use of right and left movement tabs on the keyboards make it possible to manoeuvre the track direction. By following the track in the manner described above, the user can move along the track and collect data by simply observing, counting, and measuring the desired entities as shown in Figure 4.12, Figure 4.13, Figure 4.14 and Figure 4.15, Figure 4.16 and Figure 4.17.



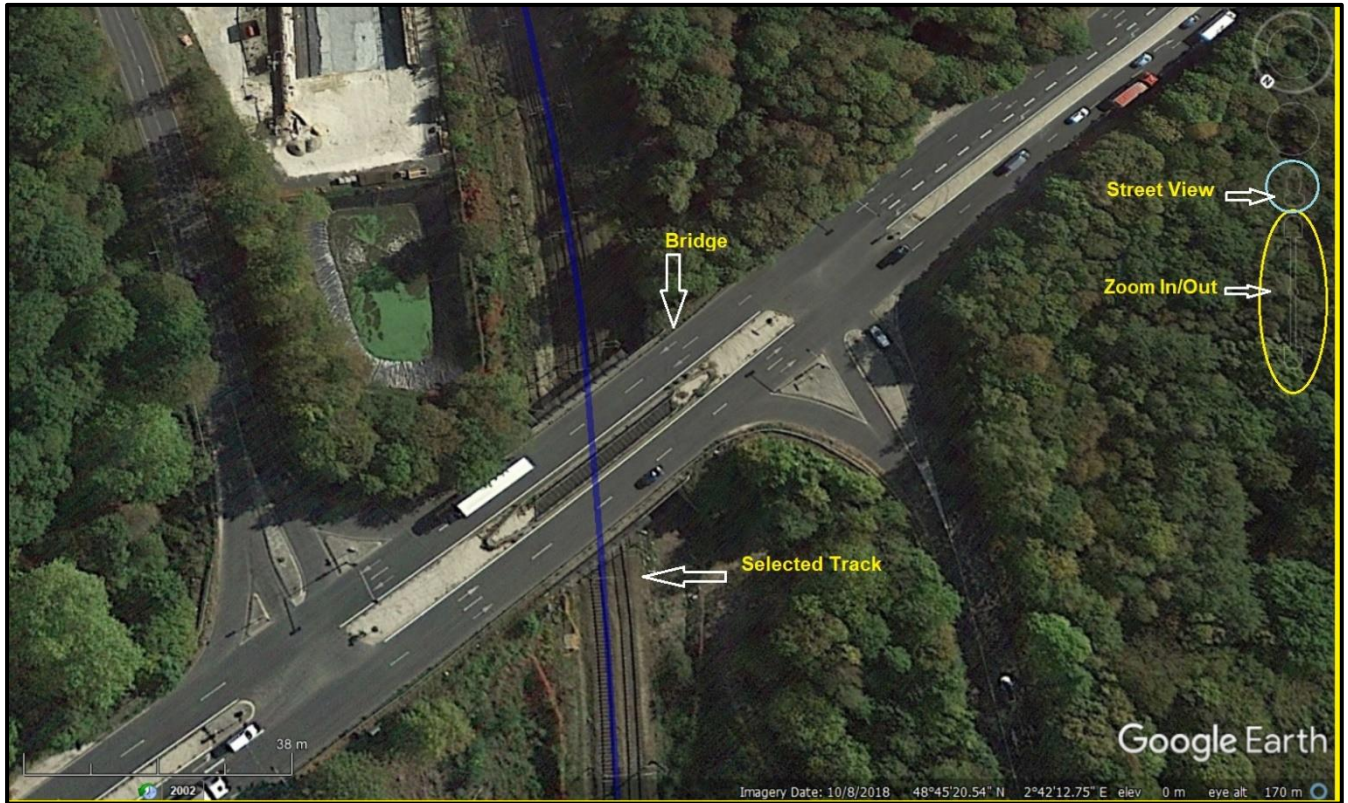


**Figure 4.12. Railway Track passing through under a bridge**

With the help of the ‘Zoom’ option, it is possible to go to any altitude above the map to observe various features on or around the selected track. It is also possible to go to the virtual street level using the ‘Street View’ option just above the zoom option on the right side of the Google Earth screen, as seen in Figure 4.13. In Figure 4.14, the same bridge of Figure 4.13 is shown through the ‘Street View’ option in which the user is virtually standing on the road bridge passing over the selected line indicated by the blue line.

One of the data that has been collected in this research work using Google Earth is Track Multiplicity. For the scope of this work, this is defined as the number of tracks running through the route per unit length. Depending upon track type (single, double, multiple) or purpose (proximity of a railway yard or station), track multiplicity changes, and can easily be observed and measured as presented in Figure 4.18.





**Figure 4.13. Selected Railway Track passing above a bridge in Map View**



**Figure 4.14. Selected Railway Track passing above a bridge in Street View**



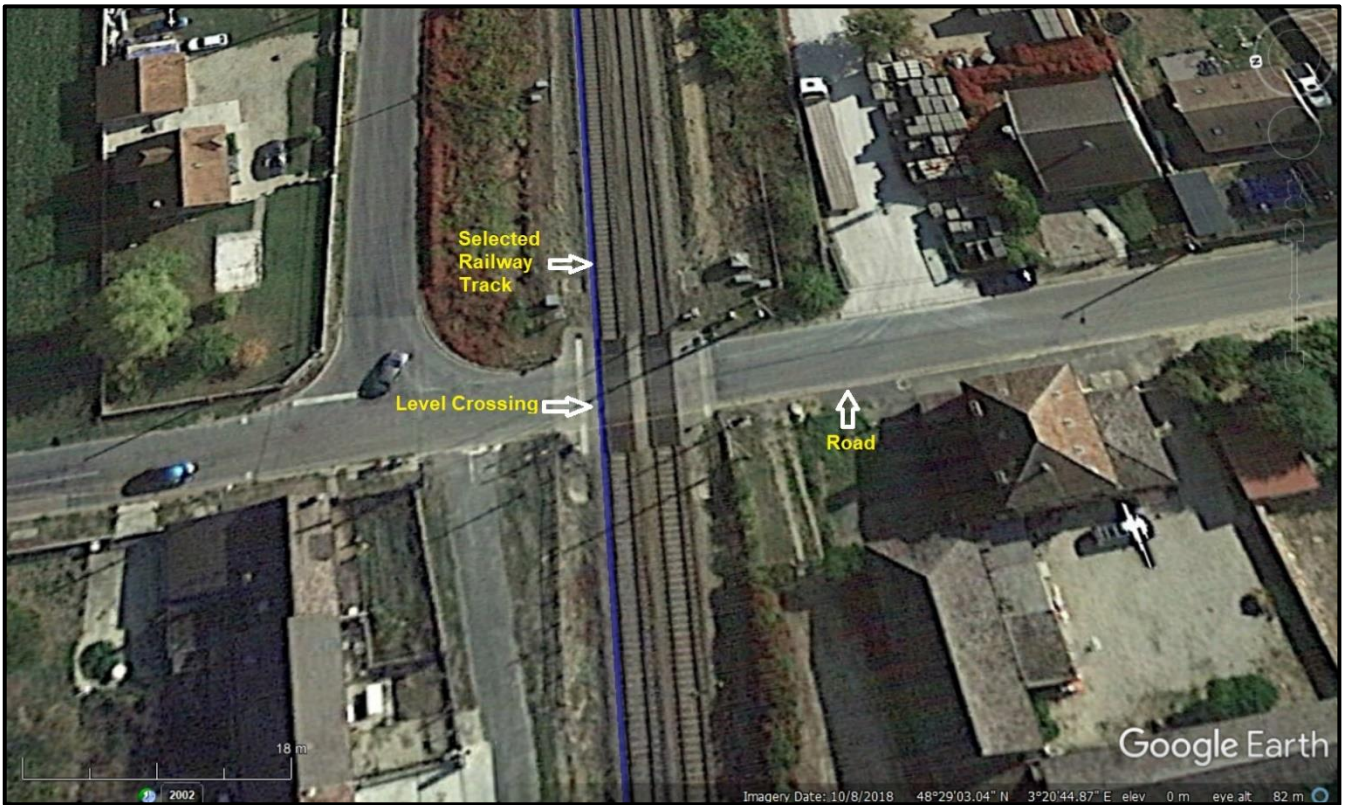


Figure 4.15. Selected Track Intersecting a road through a Level Crossing in Map View

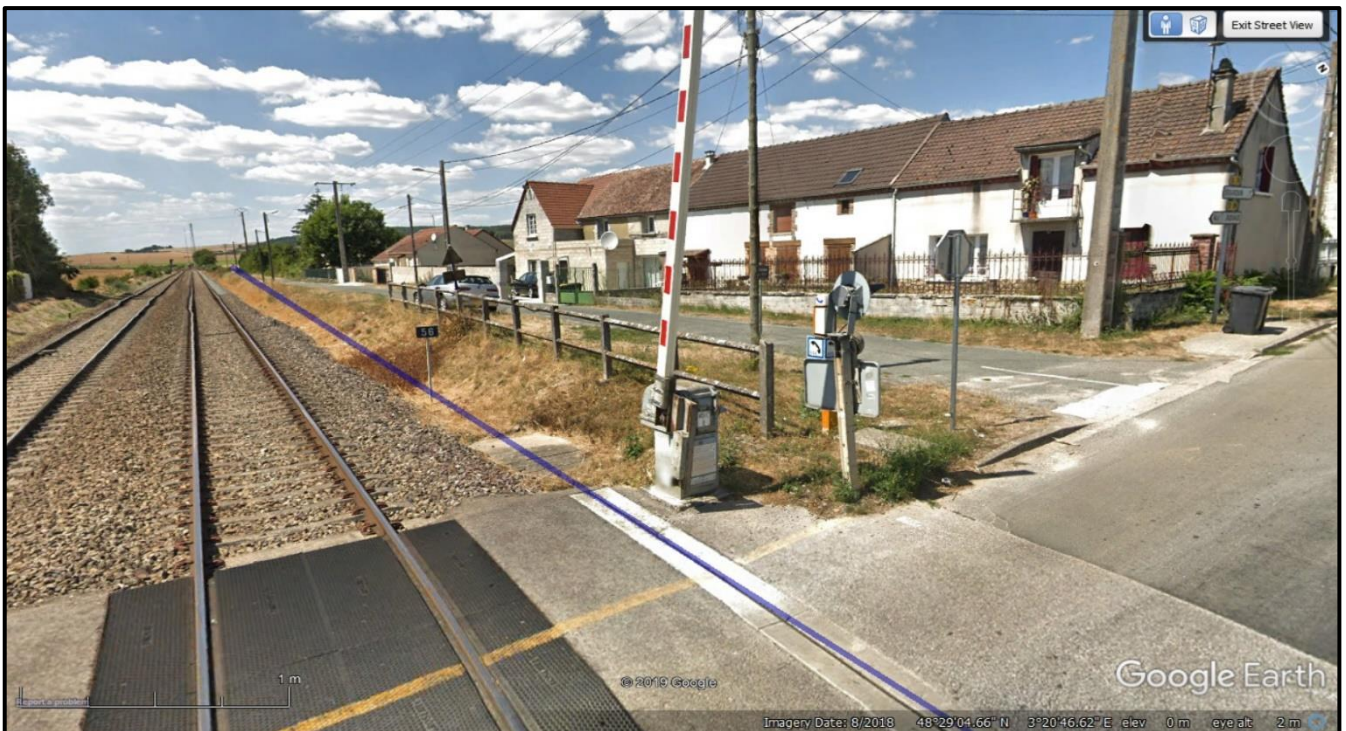
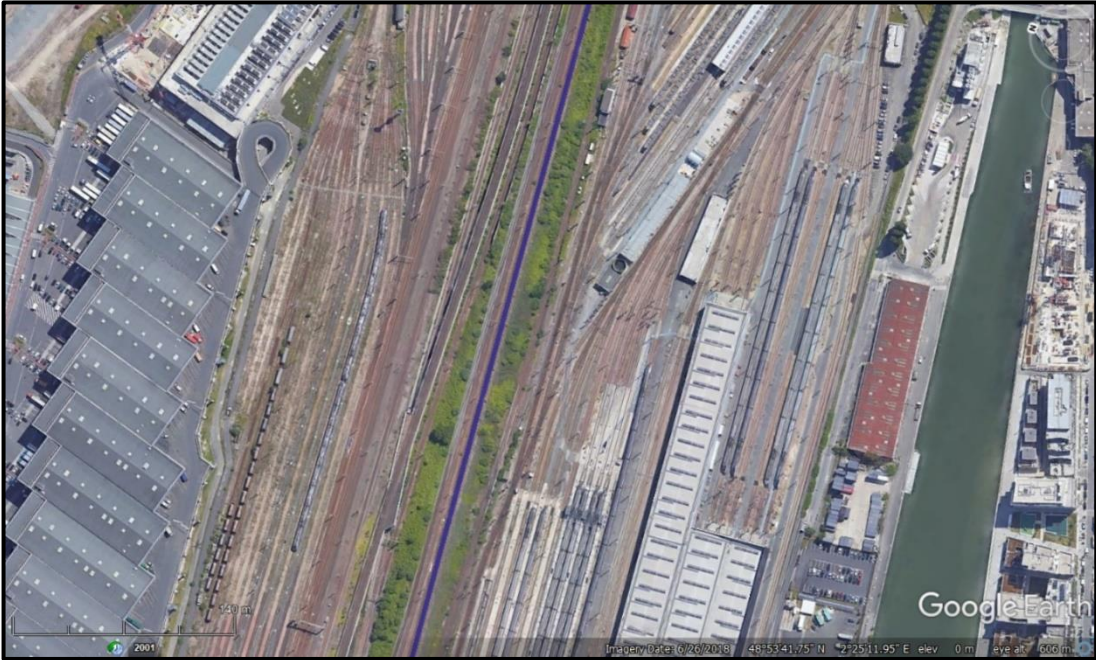
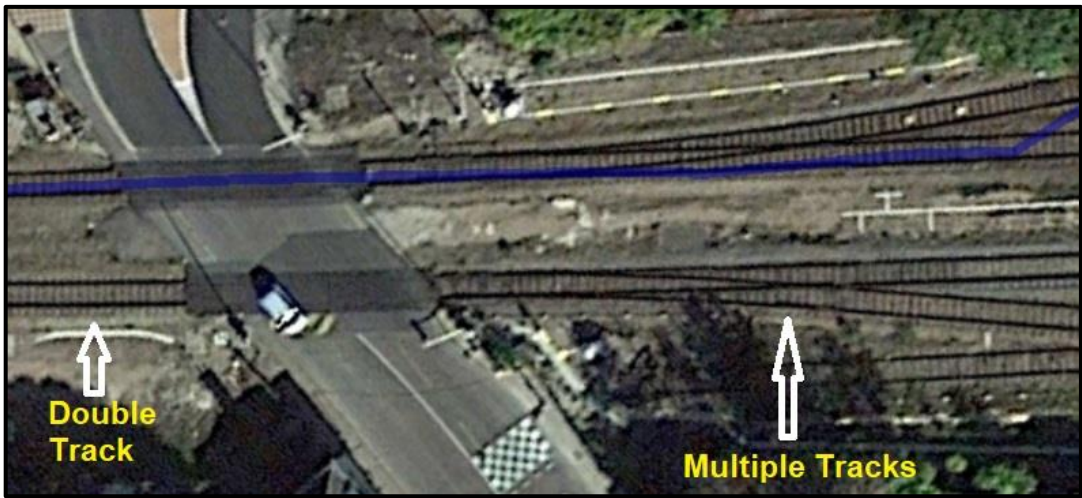


Figure 4.16. Selected Track Intersecting a road through a Level Crossing in Street View





**Figure 4.17. A Railway Yard along the Route of Selected Railway Track**



**Figure 4.18. Track Multiplicity (Google Earth Screenshot)**

**4.4.4. Measurement in Google Earth**

Another type of data that has been extracted through Google Earth is the measurement of lengths of different structures. When collecting data for the number of bridges, these were divided into two categories; (a) Long bridges, which are longer than 50 m and, (b) Short bridges, which are shorter than 50 m. It was done to simplify the stock estimation, where material intensities will be used. Similarly, along with the number of tunnels in selected

tracks, their respective lengths have also been recorded. All this was done using the measurement tool of Google Earth, as demonstrated in Figure 4.19.



**Figure 4.19. Tunnel length measurement using Google Earth**

## **4.5. Stock Estimation**

Following the data extraction for French railway infrastructure using Google Earth next step is to estimate material stock. Most of the stock present in this system is in-use stock, and the bottom-up MFA approach has been used for material estimation. The data, in this research work, has been collected in terms of the number of products i.e., bridges, level crossings, tunnels, etc.

In the bottom-up approach that is employed in this research work for material stock estimation, the number of products is then multiplied by material intensities of various materials in French Railway Infrastructure to get estimated material. Following material intensities, as extracted from literature, manufacturers, and standards, have been used.

**4.5.1. Material Intensities**

**4.5.1.1. Steel**

In the Railway Infrastructure, steel is one of the abundant raw materials used. Rails hold a significant portion of steel, which are graded by weight over a standard length in kg/m. The weight of the rail adopted on a particular track depends heavily on axle loads, traffic movement, and train speeds (Kerr, 2014). Just like most other European states, France also follows railway codes of the International Union of Railways (UIC). Three standard rail sections are used in the railway infrastructure as given by UIC. The grade of these rail sections are given in Table 4.4 (Arcelormittal, 2020; Suzhou, 2020).

**Table 4.4. UIC Rail Grade Standards (Arcelormittal, 2020; Suzhou, 2020)**

<b>Size</b>	<b>Weight (kg/m)</b>
UIC50	50.46
UIC54	54.43
UIC60	60.21

The joint system of the rails is done by fishplates, which are either 4-holes or 6-holes (Suzhou, 2020). These fish plates are used to hold two lengths of the rail tracks together, as shown in Figure 4.20. Standard weights of the fishplates as per UIC are given in Table 4.5 (AGICO, 2020). For the sake of the simplicity and ease-of-use in the estimation of the steel in French railway infrastructure, the average of the various fishplates has been taken. When calculating the unit weight of the steel in the railway track, this average is used.

A fish plate joins two rails through fish bolts. Fish bolts come in different sizes depending upon the type and holes of the fishplates. Table 4.6 presents standard fish bolts and their average for the use in the estimation part later on. In contrast, Table 4.7 summarizes other miscellaneous railway components which are used for laying the railway tracks. Their average values have been taken.



**Table 4.5. UIC Fish Plate Standards (AGICO, 2020)**

<b>Size (Length/Diameter)</b>	<b>Weight (Kg)</b>
4 hole-600/Φ28	18.07Kg
4 hole-630/Φ25	17.47Kg
4 hole	18.1Kg
6 hole-800	14.34Kg
4 hole-600/Φ28	19.94Kg
<b>Average</b>	<b>17.58</b>



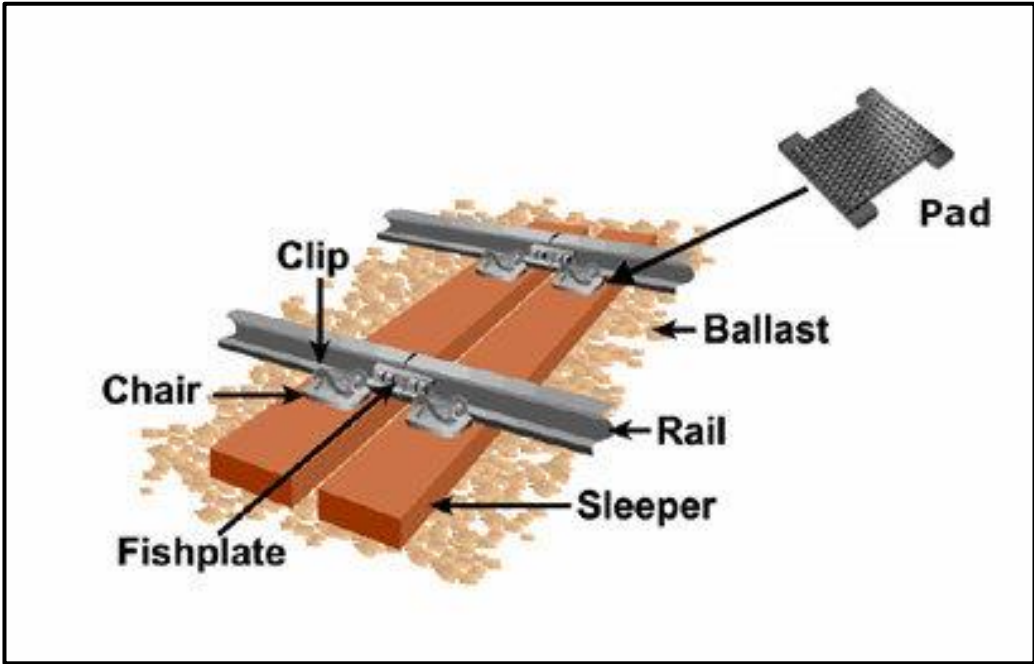
**Figure 4.20. A Fish Plate (AGICA, 2020)**

**Table 4.6. UIC Fish Bolts Standards (AGICO, 2020)**

<b>Diameter (in)</b>	<b>Length (in)</b>	<b>Weight (Kg)</b>
7/8	4-1/2	0.563
7/8	5-1/2	0.651
1	5-1/4	0.889
1	5-3/4	0.895
<b>Average</b>		<b>0.75</b>

**Table 4.7. Average Weight of Railway Track Components**

Components	Average Weight (Kg)
Rail Clip	0.76
Rail Spikes	0.56
Tie Plate	14.44
Rail Anchor	0.8
Rail Bolt	0.5
Total	17.06



**Figure 4.21. A Typical Railway Joint (Kaewunruen, 2007)**

It can be seen in Figure 4.21 that a railway joint involves four fishplates, eight fish bolts, four Railway clips, four tie plates, four rail spikes, and eight rail bolts. Using the average values, it is found that a railway joint contains 146.5 kg of steel. As far as rails are concerned, as per UIC standards, rails are available in the range of 12-25 meter per length (AGICO, 2020). Figure 4.22 shows that two rails form a track. It has been assumed that 25-meter length rails

have been used in French Railway Infrastructure. By this assumption, a 1 km run of railway tracks contains 40 joints. Using these assumptions and amount of steel calculated for a single joint amount of steel for a 1 km length of railway track has been calculated for different UIC standards given in Table 4.8.

**Table 4.8. Steel per kilometer of Railway Tracks (tons)**

Standard	Steel per 1 Km (ton)
UIC50	107
UIC54	109
UIC60	120



**Figure 4.22. Two rails form a Track (Pixabay, 2020)**

**4.5.1.2. Wood**

Wood has been used to make railway sleepers for the last two centuries. It is astonishing to note that these still form the majority of the railway sleeper in railway infrastructure today.

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Wooden sleepers are cheaper, light-weight, and easy to transport, install, and maintain. The weight of railway sleepers varies exceedingly depending upon the type and age of the tree the wood came from, the density and the specific length and profile of the sleeper. The average timber sleeper weighs around 70-110 kg (At a Glance: Railway Sleeper Materials, 2020; SIZES & WEIGHTS of Railway Sleepers, 2020).

The number of sleepers per rail length is called sleeper density. It is specified as  $M+x$  where  $M$  the length of the rail in meters and  $x$  is a number that varies according to factors such as type and section of rail tracks, type of ballast and ballast cushion, axle load and speed, type and strength of the sleepers and nature of formation. The spacing of sleepers is kept fixed depending upon the sleeper density. Spacing is not maintained uniform throughout the rail length. It is usually narrower near the joints because of the weakness of the joints and the impact of moving loads on them.

The number of sleepers in a track can also be specified by indicating the number of sleepers per kilometer of the track. Based upon the type of tracks and design of the track this value varies from 1340 sleepers per kilometer to 1660 sleepers per kilometer (Sleeper Density and Spacing of Sleepers, 2020). In any case, minimum sleeper density is kept at 1340 sleepers per kilometer (India, 2020). Table 4.9 shows the amount of wood per kilometer for sleepers by assuming the average weight of sleeper as 70-110 kg.

**Table 4.9. Wood per kilometer of Railway Tracks (tons)**

<b>Sleeper Density per Kilometer</b>	<b>Wood Quantity per Kilometer (tons)</b>
1340	94-147
1540	108-169
1660	116-183



**4.5.1.3. Ballast**

Ballast exists in the railway infrastructure in the form of railway bedding. Its main function is to furnish solid ground for railroad tracks and to provide track stability, drainage, and axle load distribution into the ground beneath (CCAA, 2020). It also prevents vegetation growth on the track. Thus, the ballast layer is a very vital component of the conventional railway track. Its importance has grown with increasing axle loads and train speeds (Nålsund, 2014).

The quantity of ballast depends upon the gauge of the track. The wider gauge requires broader formations, hence, a wider layer of the ballast. The depth of the ballast also varies with the density of railway traffic (Nasir, 2020). The thickness of the ballast layer also depends on the size and spacing of the sleepers, the amount of traffic expected on the line, and various other factors (CCAA, 2020). Table 4.10 summarizes the quantity of ballast in one kilometer for different types of lines (Light-Railways, 2020; Nasir, 2020; ARTC, 2020).

**Table 4.10. Ballast per kilometer of Railway Tracks (tons)**

Type	Ballast Quantity per Km (tons)
ASCE60	969
ASCE41.5	647
ASCE30	456

**4.5.1.4. Concrete**

Concrete sleepers are extensively used in the construction of High-speed Railway, and currently, many countries already have concrete sleepers in high-speed passenger line. The stability of concrete sleepers is much higher than wood sleepers. They also have many advantages e.g., longer lifespan, high stability, small maintenance requirement, low damage rate, and low scrap rate. On the other hand, they also have a few disadvantages e.g.,

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heavyweight, difficulty in transport, and environmental limitations (AGICO, 2020). Concrete sleepers contribute to only a small fraction of the railway infrastructure in the US, in Europe and Japan, but in many parts of the world, concrete sleepers are gaining importance since the last 50 years or so (Railway, 2020).

The average wooden sleeper weighs around 70 kg to 110 kg, while an equivalent concrete sleeper might weigh about 350 kg (Railway, 2020). There are several factors that play a role in deciding the weight of the concrete sleeper. Based on those factors, there is a huge of sleepers based upon their weight. The weight of a single sleeper can range from 138 kg to as heavy as 700 kg per sleeper (Railone, 2020; BrainKart, 2020).

Table 4.11 shows the amount of concrete material per kilometer in sleepers by assuming the average weight of sleeper as 138-700 kg for different sleeper densities.

**Table 4.11. Concrete per kilometer of Railway Tracks (tons)**

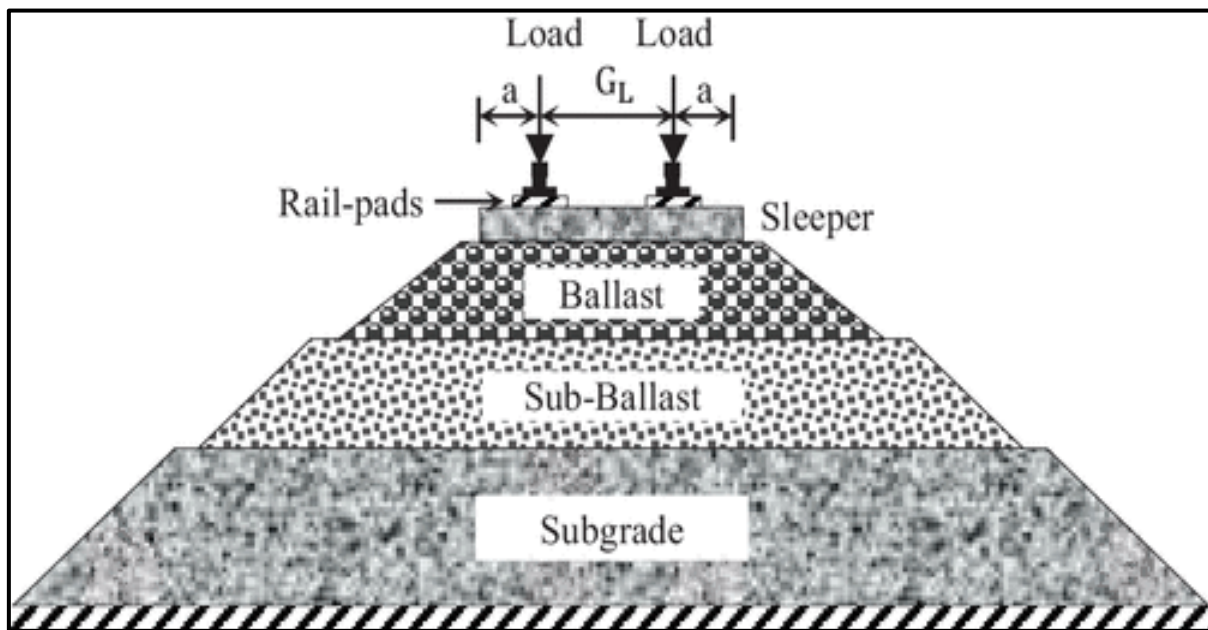
<b>Sleeper Density per Kilometer</b>	<b>Concrete Quantity per Kilometer (tons)</b>
1340	185-938
1540	213-1078
1660	229-1162

**4.5.1.5. Subgrade Soil**

One of the most important components of any railway infrastructure is the subgrade soil, which provides a stable platform for the track substructure i.e., ballast and track (Nie, 2018). The role of the subgrade soil in the railways is similar to that of a foundation in a building. It is responsible for the transfer of the applied loads of the rail to the ballast bed and then ultimately to the subsoil ground (Trackopedia, 2020).

The subgrade soil is generally the naturally occurring soil (Railengdigest, 2020). Generally speaking, on a broad perspective, the soil type of France is predominantly clayey (Britannica, 2020; Lawr, 2020). Based upon different soil conditions and admixtures of other soil types, the density of clayey soils falls in the range of  $1260 \text{ kg/m}^3$  to  $1500 \text{ kg/m}^3$  (Structx, 2020).

Apart from the type of soils and their respective soil densities, several parameters affect the material intensities of the subgrade soils in railway infrastructure. One of those parameters is the height of the formation of the subgrade layer. Depending upon the type of soil and other design requirements, this subgrade soil i.e., formation height varies. Based on specific design codes, a layer height of 0.6m to 1m is prescribed. Similarly, depending upon the gauge of the track, ballast layer, and site condition, the width of the formation has to be adjusted accordingly. In most cases, it is kept between 5.25m and 7.85m at the top, and it is more at the base, generally 12m to 20m, depending upon side slope and the height of the formation as can be seen in Figure 4.23 (Formation, 2020).



**Figure 4.23. Cross-section of a typical Railway Track (Kumawat, 2019)**

Keeping all the above information in mind, subgrade soil intensity for a unit length of the track has been computed by making suitable assumptions. Material intensity for subgrade soil

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per kilometer length of the track, by considering a higher and an upper range of values as mentioned in the previous paragraphs, come out to be in the range of 6521 kt to 20888 kt. The detailed calculation of these values is given in Appendix B.

### **4.5.2. Estimation**

Above material intensities have been multiplied with the respective number of products to estimate the related stock quantity in the system using Eq. 5.

$$MS_m = \sum L \cdot I_m \dots\dots\dots \text{(Eq. 5)}$$

Where,

$MS_m$  = Material Stock quantity for material  $m$

$L$  = Length of the track

$I_m$  = Material intensity of material  $m$  per Kilometer

## **CHAPTER 5**

# **INPUT DATA INTERPRETATION AND DISCUSSION**

Previous chapters provided the basis for a thorough comprehension of the research topic, its need, and its scope in the global context. This understanding helped in developing the novel method for catering data deficiencies in Material Flow Analysis (MFA) by utilization of Google Earth as a data extraction tool. The complete method, description of the French railway infrastructure, and data sampling criteria along with step-by-step procedure, have already been described in the previous chapter.

This chapter presents the French railway infrastructure data, which has been extracted using Google Earth. The data that has been directly extracted from Google Earth is then used to verify the newly developed method by comparing it with SNCF statistical data. Further, this input data has been used for material stock estimation within this system by employing the bottom-up approach using material intensities for railway infrastructures. It also includes a detailed discussion and interpretation of the extracted data and material stock estimation.

## 5.1. Track Data Extracted from Google Earth

The model that has been developed in this research proposes to extract data from the French Railway infrastructure using Google Earth. There is a lot of data that can be obtained from this infrastructure. The data that has been extracted was selected to serve two purposes; (a) verification of the method by comparison with SNCF statistical data and, (b) estimation of the material stock within the French railway system. First of all, the type of tracks, as described in Table 4.1, and track identification numbers are collected using the SNCF map to identify the track and differentiate them from other tracks.

For method verification purposes, data related to the number of bridges and number of level crossings have been extracted for each of the selected tracks. These entities, as described in Section 4.2, have been used to verify this novel approach by comparing them with their corresponding values from SNCF statistical data. The number of tunnels for each selected track has also been extracted. The total length of the tunnels existing in a particular track length has been then calculated by simply adding the length of each tunnel for that particular track.

Using Google Earth, the lengths of the tracks have been extracted for material stock estimation purposes. Track lengths have been extracted in terms of the number of railway lines, i.e., single track, double track, and multiple tracks. Since multiple tracks vary in the number of tracks for different sections of a single track, so a parameter 'track multiplicity' has been introduced in which an average of the number of tracks running for cumulated length has been calculated by taking weighted averages.

The following section summarizes the whole input data as extracted from the French Railway infrastructure using Google Earth. Discussion and interpretation of extracted data have also been given to make the reader thoroughly understand the significance and importance of the data.

**Table 5.1. Data Extracted for Mixed Electrified Railway Tracks**

Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	Km
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>Km</i>
1	MED	420	647	-	550.5	96.5	9	80	523	167	0	0
2	MED	590	548	-	502	46	7	54	401	159	0	0
3	MED+MEM	070	492	-	374	118	15	115	235	95	11	8.2
4	MED	640	477	-	411.6	65.4	10	112	270	213	7	1.7
5	TGV	005	401	-	388.2	12.8	3	151	223	0	1	4
6	MES+MED	650	321	-	302.3	18.7	9	85	133	240	4	1.8
7	MED+MEM	272	253.5	-	164.4	89.1	7	44	155	69	0	0
8	MED+MEM	930	252	-	204	48	6	98	209	14	22	18.6
9	MED	515	243	-	214.5	28.5	9	48	161	117	2	0.2
10	MED	655	231	-	203	28	14	68	89	61	5	2.25
11	TGV	226	215	-	204.5	10.5	4	30	165	0	3	1
12	MES	672	150.5	142.9	-	7.6	4	36	86	89	0	0

Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	Km
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>Km</i>
13	MES+MED	850	144	78	53	13	5	41	80	37	13	9.8
14	MED	890	143	-	121	22	7	35	51	52	8	7.5
15	TGV	216	136	-	121.7	14.3	8	15	110	0	2	22.75
16	MED	267	123	-	103.3	19.7	6	12	80	72	0	0
17	MED	860	114	-	102.7	11.3	7	23	55	46	0	0
18	MED	321	114	-	109	5	5	21	65	44	2	2
19	MED	295	108	-	99.5	8.5	13	24	48	74	0	0
20	MED	450	98.1	-	89.1	9	6	66	47	7	0	0
21	MED+MNS	289	73.5	25.7	36.5	11.3	9	44	30	50	0	0
22	MED	468	71.7	-	68.4	3.3	5	16	31	33	2	0.8
23	MES	669	60.5	56	-	4.5	3	13	37	35	2	1.6
24	TGV	226310	40.5	-	30.5	10	4	26	27	0	1	2.25
25	MED	656	31.9	-	31.9	0	-	5	12	22	1	0.3



Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	Km
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>Km</i>
26	MES	390	29	26.2	2.2	0.6	11	7	12	13	0	0
27	MES	875	28.5	28	0	0.5	6	2	9	17	0	0
28	MED	849	28	-	23	5	6	6	7	13	0	0
29	MES	446	17.5	17	-	0.5	3	2	4	15	0	0
30	MED	657	16	-	15.3	0.7	9	2	8	18	0	0
31	MED	269	14.6	-	12.6	2	4	3	8	9	0	0
32	MED	278	11	-	8.5	2.5	15	11	11	0	0	0
33	TGV	226306	10	-	10	-	-	8	0	0	0	0
34	MED	142	9	-	4.5	4.5	7	6	16	0	0	0

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Table 5.1 summarizes the data extracted for mixed railway tracks, which are electrically operated. These are 34 railway lines, which comprise almost 35% of all the sample railway lines covering a total of 5652.8 Km of the railway tracks. This is the largest group of tracks amongst the sample tracks and accounts for 61.5% by the length of the sample tracks length considered for this research work. It also represents around one-fifth of the total French Railway infrastructure length. It should be noted that this is the most abundant category of tracks spread throughout the French Railway System.

There are 18 Mixed Electrical Double (MED) railway tracks while there are five fast trains (TGV). The rest of them are either Mixed Electrical Single (MES) tracks or a combination of all of the above. There are three tracks that also include a significant portion of Mixed Electrical Multiple (MEM) tracks in which three or more than three parallel tracks run for a considerable length. This aspect is considered because the occurrence of such multiple tracks exhibit an abundance of material stock and significantly alter their magnitude. It should also be noted that all of these MEM occurrences are happening from Metropolitan cities such as Paris, Strasbourg, Lille, Marseille, and Bordeaux, etc.

There are six railway tracks falling in Category-A, as described in section 4.3.1, which are more than 300 Km long. On the other hand, 13 tracks belong to Category-B while the rest of them fall into Category-C (less than 100 Km length). The longest track is 647 Km while the shortest of them is only 9 Km long. In terms of length, 373.8 Km (6.5% of mixed electrical tracks sample) of railway tracks are single tracks, while 717.3 Km (12.6%) are multiple tracks. The most significant part of the mixed electrical tracks sample consists of a double-track covering 4561.7 Km, which is almost 80% of the sample.

The above sample of 34 tracks has 4707 railway bridges out, which 1309 are larger bridges (higher than 50 m length) while the rest of them are smaller bridges. Based upon Eq. 1, Km per bridge ( $K_{BG}$ ) for this category comes out to be 1.20. Similarly, there are 1781 level crossings coming in the way of sample tracks of this mixed electrical railway track category. Using Eq. 2,  $K_{LG}$  for this category turns out to be 3.17. As far as the data related to tunnels is

## INPUT DATA INTERPRETATION AND DISCUSSION

concerned, 86 tunnels covering a length of around 85 Km have been spotted while using Google Earth.

The summary of the critical numeric information from Table 5.1 has been put into Table 5.2 to understand better the parameters, their relevance, and their numeric value in a more convenient way so that it can be compared to or related in the coming sections of this research work.

**Table 5.2. Data Summary for Mixed Electrified Tracks**

Parameter	Unit	Value
No. of tracks	No.	34
Percentage of sample Track selected	%	35
Length covered	Km	5652.8
Percentage of total sample length	%	61.5
Single Line	Km	373.8
Double Line	Km	4561.7
Multiple Line	Km	717.3
Longest Track	Km	647
Shortest Track	Km	9
No. of Bridges	No.	4707
$K_{BG}$ , (Km/Bridge for this category)	-	1.20
No. of Level Crossings	No.	1781
$K_{LG}$ , (Km/Bridge for this category)	-	3.17
No. of Tunnels	No.	85

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Similarly, Table 5.4 presents the extracted data from Google Earth for the mixed non-electric railway. These are 22 railway lines, which comprise around 23% of all the sample railway lines. These cover a total of 2859.1 Km of the selected sample railway tracks and accounts for almost 31% by the length of the total sample tracks length considered for this research work. In terms of the total French Railway System track length, it represents around 10% percent of the total French Railway infrastructure length.

In this category, there are five Mixed Non-Electrical Double (MND) railway tracks, while there are 12 Mixed Non-Electrical Single (MNS) tracks. There are five selected tracks which are a combination of different types of tracks.

Concerning the length of the tracks, only one selected railway track falls in Category-A, which is more than 300 Km long. There are seven tracks belong to Category-B while the rest of them fall into Category-C. The longest track is 490 Km while the shortest of them is only 14 Km long. In terms of length by type of track, 1319.6 Km of railway tracks are single tracks that account for just less than half of the tracks of this category. 1243.4 Km (around 44%) are belonging to the double tracks category while 296.1 Km (almost 10%) are multiple tracks.

There are 2048 railway bridges coming along the way of selected mixed non-electric category, out of which 552 are longer bridges (greater than 50 m length) while 1496 are smaller bridges. Based upon Eq. 1, Km per bridge ( $K_{BG}$ ) for this category comes out to be 1.39. Similarly, there are 1562 level crossings coming in the way of sample tracks of this mixed electrical railway track category. Using Eq. 2,  $K_{LG}$  for this category turns out to be 1.83. There are 55 tunnels covering a length of little above 28 Km.

As for the Mixed Electric Lines, the summary of the key numeric information, as collected from Google Earth, for Mixed Non-Electric Selected Railway tracks has been put into Table 5.3 for better understanding and later referencing and comparison purposes.

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**Table 5.3. Data Summary for Mixed Non-Electrified Tracks**

Parameter	Unit	Value
No. of tracks	No.	22
Percentage of sample Track selected	%	23
Length covered	Km	2859.1
Percentage of total sample length	%	31
Single Line	Km	1319.6
Double Line	Km	1243.4
Multiple Line	Km	296.1
Longest Track	Km	490
Shortest Track	Km	14
No. of Bridges	No.	2048
K <sub>BG</sub> , (Km/Bridge for this category)	-	1.39
No. of Level Crossings	No.	1562
K <sub>LG</sub> , (Km/Bridge for this category)	-	1.83
No. of Tunnels	No.	55

**Table 5.4. Data Extracted for Mixed Non-Electrified Railway Tracks**

Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	Km
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>Km</i>
1	MND	001	490	-	424	66	9	104	268	151	7	6.1
2	MNS+MED	905	285	136.8	115	33.2	6	104	77	131	35	11.5
3	MNS	722	279.5	260.8	-	18.7	4	38	188	187	0	0
4	MED+MND	530	254	-	240	14	8	53	107	187	0	0
5	MNS	718	249	212.9	27.6	8.5	5	43	174	143	4	4.2
6	MNS	631	142	132.5	-	9.5	4	27	81	92	0	0
7	MNS	702	124	113.7	-	10.3	4	18	77	72	2	2.3
8	MND	145	123	-	113.9	9.1	11	7	16	45	0	0
9	MNS	629	99.5	92.8	-	6.7	3	11	59	63	0	0
10	MND	561	96.6	-	90.6	6	7	17	61	54	0	0
11	MNS	604	95.5	89	-	6.5	4	13	54	63	0	0
12	MNS+MED	110	87.2	23.3	54.9	9	5	10	72	38	3	2.6

Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	No.
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>		
13	MNS+MND	648	83.5	72.5	7.6	3.4	5	15	43	62	0	0
14	MND	441	80.8	-	2.5	78.3	7	14	39	42	0	0
15	MNS	723	78	75.4	-	2.6	4	16	40	40	0	0
16	MND	783	72.4	-	68.4	4	6	17	37	34	0	0
17	MND+MED	372	59	-	55.9	3.1	6	15	30	23	4	1.4
18	MNS	725	44	-	42	2	5	10	29	24	0	0
19	MNS	606	43.6	40.2	-	3.4	3	8	24	29	0	0
20	MNS	486	38	36.2	-	1.8	4	8	11	32	0	0
21	MNS	379	20.5	20.5	-	-	-	2	8	26	0	0
22	MNS	296	14	13	1	-	-	2	1	24	0	0

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Table 5.6 gives insight into extracted data for electric freight railway tracks category, which were selected for this research work. In total, ten railway lines were chosen for the said category, which accounts for less than 2% of all the sample railway lines. These cover a total of 158.3 Km of the selected sample railway tracks. The reason for such a low percentage and the number of tracks is the fact that it is the most less frequent type of track appearing in the French Railway Infrastructure. Such tracks are usually built for a very short distance just to deliver goods to and from the commercial hubs. For this category, there were selected seven Freight Electrical Double (FED) railway tracks, while the other three were Freight Electrical Single (FES) tracks.

For the lengths of the tracks, none of the selected railway track falls in Category-A or Category-B. All of them fall into Category-C. The longest track is 34 Km, while the shortest of those selected was only 6.5 Km long. In terms of length by type of track, 41.8 Km of railway tracks are single tracks, which accounts for almost one-fourth of the tracks of this category. 101 Km (around 64%) are belonging to the double tracks category while only 15.5 Km (nearly 10%) are multiple tracks.

There exist 134 railway bridges along the route of the tracks of the selected category out, of which 55 are larger bridges (greater than 50 m length) while 79 are smaller bridges. Based upon Eq. 1, Km per bridge ( $K_{BG}$ ) for this category comes out to be 1.18. Similarly, there are 40 level crossings coming in the way of sample tracks of this freight electrical railway track category. Using Eq. 2,  $K_{LG}$  for this category turns out to be 3.95. There are only two tunnels covering a short length of 1.4 Km.

The summary of the key numeric information, as collected from Google Earth, for selected Freight Electric Railway tracks has been recorded into Table 5.5 so that these values may be used for better understanding and later referencing and comparison purposes.



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**Table 5.5. Data Summary for Freight Electrified Tracks**

<b>Parameter</b>	<b>Unit</b>	<b>Value</b>
No. of tracks	No.	10
Percentage of sample Track selected	%	2
Length covered	Km	158.3
Percentage of total sample length	%	1.7
Single Line	Km	41.8
Double Line	Km	101
Multiple Line	Km	15.5
Longest Track	Km	34
Shortest Track	Km	6.5
No. of Bridges	No.	134
K <sub>BG</sub> , (Km/Bridge for this category)	-	1.18
No. of Level Crossings	No.	40
K <sub>LG</sub> , (Km/Bridge for this category)	-	3.95
No. of Tunnels	No.	2

**Table 5.6. Data Extracted for Freight Electrified Railway Tracks**

Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	Km
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>Km</i>
1	FED	177	34	-	29.5	4.5	4	7	17	5	1	0.8
2	FED	159	26.5	-	24.5	2	4	4	15	4	0	0
3	FED	232	20.3	19.8	-	0.5	14	3	11	9	0	0
4	FES	362	18	15.5	-	2.5	25	10	9	8	1	0.6
5	FED	174	14	-	12.5	1.5	3	3	9	3	0	0
6	FED	192	12.5	-	10	2.5	17	15	6	2	0	0
7	FED	935901	11.2	-	11.2	-	-	2	4	5	0	0
8	FES	180611	8.5	-	6.5	2	3	8	3	0	0	0
9	FED	247	6.8	-	6.8	-	-	2	4	4	0	0
10	FES	935903	6.5	6.5	-	-	-	1	1	0	0	0

**Table 5.7. Data Extracted for Freight Non-Electrified Railway Tracks**

Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	Km
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>Km</i>
1	FNS	010	56.5	53	2	1.5	5	4	6	62	0	0
2	FNS	013	52	50.5	0.5	1	6	3	7	37	0	0
3	FNS	012	43	41.5	-	1.5	4	3	15	40	0	0
4	FNS	210	41.5	38.5	-	3	6	3	7	42	0	0
5	FNS	030	28.5	27.5	-	1	5	4	12	21	0	0
6	FNS	649	25.5	24	-	1.5	3	9	18	25	0	0
7	FND	790	24	-	24	-	-	9	21	13	0	0
8	FNS	928	23.5	22.8	0.3	0.4	4	10	26	9	0	0
9	FNS	904	21.5	21	-	0.5	3	2	7	27	0	0
10	FNS	681	19	18	-	1	4	1	4	28	0	0
11	FNS	785	18	15.5	1.5	1	6	2	12	16	0	0
12	FNS	782	16.5	15.2	-	1.3	4	4	10	19	1	0.2

Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	Km
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>Km</i>
13	FNS	867	16.2	15.6	-	0.6	5	3	5	17	0	0
14	FNS	253	16	15	-	1	4	2	5	19	0	0
15	FNS	002	16	15	-	1	4	1	3	10	0	0
16	FNS	356	15.5	15.5	-	-	-	3	8	14	0	0
17	FNS	865	14.3	13.5	-	0.8	4	2	3	16	0	0
18	FNS	262	10.5	9.5	-	1	5	1	2	17	0	0
19	FNS	789	9	7.5	-	1.5	4	1	4	5	0	0
20	FNS	868	8	8	-	-	-	0	1	10	0	0
21	FNS	889	6.3	6	-	0.3	5	0	2	9	0	0
22	FNS	935606	6.1	5.2	-	0.9	10	1	2	3	0	0
23	FNS	935902	5.5	4.2	-	1.3	10	1	2	3	0	0
24	FNS	786	5.2	4	-	1.2	6	2	4	8	0	0
25	FNS	294	4.5	4.2	-	0.3	4	1	1	5	0	0

Sr. No.	Track Type	Track Identity No.	Length	Single Track Length	Double Track Length	Multiple Track Length	Average Track Multiplicity	Large Bridges (>50 m)	Small Bridges (<50 m)	Level Crossings	Tunnels	
											No.	Km
-	-	-	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>Km</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>No.</i>	<i>Km</i>
26	FNS	935904	3.5	3.5	-	-	-	1	1	1	0	0
27	FNS	780	3.1	2	-	1.1	12	0	1	5	0	0
28	FNS	935111	2	0.5	-	1.5	6	1	2	3	0	0
29	FNS	796	1.3	1	-	0.3	4	0	0	0	1	0.15

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Table 5.7 provides the extracted data for freight railway tracks, which are operated non-electrically. There are 29 railway lines which have been selected for this category. This Freight Non-Electrified Railway Tracks category is the 2<sup>nd</sup> largest category of tracks by number amongst the sample tracks and accounts for 30.5% by the number of the sample tracks length considered for this research work. These cover a total of 512.5 Km of the railway tracks that accounts for less than 6% by the length of the sample tracks length.

There is hardly any double or multiple track types in this category, but most of them are single-track type. Hence, all of the selected railway tracks are Freight Non-Electric Single (FNS), while only 1 Freight Non-Electric Double (FND) track has been considered.

Just like Freight Electric Tracks, none of the selected railway track falls in Category-A or Category-B. All of them fall into Category-C. The longest track is 53 Km, while the shortest of those selected is merely 1 Km long. In terms of length by type of track, 457.7 Km of railway tracks are single tracks, which account for almost 90% of the tracks of this category. 28.3 Km (around 5.5%) are belonging to the double tracks category while 26.5 Km (nearly 5.2%) are multiple tracks.

This category of tracks has 265 railway bridges out, which 74 are larger bridges (greater than 50 m length) while the rest of them are smaller bridges. Based upon Eq. 1, Km per bridge ( $K_{BG}$ ) for this category comes out to be 1.93. Similarly, there are 484 level crossings coming in the way of sample tracks of this mixed electrical railway track category. Using Eq. 2,  $K_{LG}$  for this category turns out to be 1.06. As far as the data related to tunnels is concerned, there exist only two tunnels covering less than a half kilometer in total.

The summary of the key numeric information from lengthy Table 5.7 has been briefly recorded into Table 5.8. It is done for better understanding of the parameters, their relevance and their numeric value in a more convenient way so that it can be compared to or related in the coming sections of this research work.

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**Table 5.8. Data Summary for Freight Non-Electrified Tracks**

Parameter	Unit	Value
No. of tracks	No.	29
Percentage of sample Track selected	%	30.5
Length covered	Km	512.5
Percentage of total sample length	%	6
Single Line	Km	457.7
Double Line	Km	28.3
Multiple Line	Km	26.5
Longest Track	Km	53
Shortest Track	Km	1
No. of Bridges	No.	265
K <sub>BG</sub> , (Km/Bridge for this category)	-	1.93
No. of Level Crossings	No.	484
K <sub>LG</sub> , (Km/Bridge for this category)	-	1.06
No. of Tunnels	No.	2

## 5.2. Data Description and its Summary

Table 5.9 presents a summary of the data collected using Google Earth. Out of 468 railway tracks in French railway infrastructure, data for 95 different tracks were gathered. This data collected for selected tracks represents around one-fifth of the total tracks in the French railway network. From the number point of view, it may appear that selected tracks can represent the lesser percentage of the total number of tracks of the railway infrastructure, but the fact is that the majority of the lengthy and significant tracks have been taken in to account. Remaining left out tracks are either mostly concise length tracks or those running parallel to selected tracks for shorter distances or branch lines originating from or converging to those selected significant tracks. This explanation becomes more evident from the total length of the selected tracks. The full length of the tracks chosen for what data have been collected using Google Earth amount to just less than 9200 km. It is more than 31.5% of the total length of the French railway infrastructure. For the stipulated resources of this research work and the level of cumbersomeness faced during data collection, this percentage allows fair, if not best, the opportunity to analyse this newly developed data collection method.

**Table 5.9. A Summary of Data Collected using Google Earth**

<b>Sr. No.</b>	<b>Entity</b>	<b>Unit</b>	<b>Quantity</b>
1	Number of Tracks Covered	No.	95
2	Total Length of the Track Covered	km	9182.7
3	No. of Large Bridges ( $\geq 50\text{m}$ )	No.	1990
4	No. of Short Bridges ( $< 50\text{m}$ )	No.	5164
5	Total No. of Bridges	No.	7154
6	No. of Level Crossings	No.	3867
7	No. of Tunnels	No.	145
8	Length of the Covered Tunnels	km	114.95



## INPUT DATA INTERPRETATION AND DISCUSSION

It can be observed from Table 5.9 that the bridges have been classified into two distinct categories based upon their span length; (a) short bridges (<50 m) and (b) large bridges ( $\geq 50$  m). Although there are no general criteria of making a 50-meter mark as a dividing line, in general, as observed while collecting data, most of the railway bridges crossing over the road tend to be shorter than 50 m in most of the cases. Hence, it can be assumed, for the sake of simplification purposes, while performing material estimation, that shorter bridges are the railway bridges crossing over the road. In contrast, while the larger ones are road bridges passing over the railway track. It should also be noted that all of the bridges existing on a selected line, whether railway bridge or a road bridge, have been taken in to account for the simplification purpose leaving behind the debate whether a particular bridge is part of the railway infrastructure or the road network. In total, 7154 bridges were recorded while collecting data, of which 1990 were large bridges while 5164 were shorter ones.

There are 3867 level crossings where a railway track intersects with a road. There exist 145 tunnels for the length of data collected for the selected railway lines, which run for almost 115 km of the covered railway tracks.

### **5.3. Data Representativeness**

The most critical aspect of any data collection for the analysis purpose is the fact that whether the collected data is representative or not. Given the stipulated resources of this research work, it was not possible to obtain desired data for complete French railway infrastructure. For the data to best produce the generalized results, it was tried to make the data as representative as possible.

As explained in the previous chapter, based upon working, the number of lines and operation there are various types of railway lines in the French Railway System. Based on working, there are electrified and non-electrified railway lines. Out of 95 selected tracks, 44 are electrified while remaining are non-electrified. It is mentioned in Chapter 4, almost half of the total length of the French railway lines work on electricity. This trend reflects in the sample of

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the selected railway tracks, as more than half of the selected tracks (63%) are electrified. Similarly, more than 55% of the French railway network consists of the Double Line railway track. Of selected railway tracks for this research work, a comparable percentage of 64% represents the Double railway lines. As far as the operation is concerned, there are two types of railway tracks in the French railway system; (1) *Mixed Lines* that operate both passengers as well as freight trains and (2) *Freight Line* that run freight trains only. Given the fact that there are more mixed lines than the freight lines in the French railway network, 54 out of 95 selected railway tracks are mixed lines were 41 are freight lines.

France is a geographically diverse country that is divided into 13 metropolitan regions located in mainland Europe. Some of these regions are mountainous, while others are plain lands. Apart from the terrain, the population density of these regions is also different from each other (Britannica, 2020). In order to make data representative, an appropriate representation of all of the regions has been considered during selection of the railway lines for the data collection. Minimum three railway tracks have been selected from each region while giving more weightage to the more population-dense and significant regions considering greater railway network spread in them. For example, for *Île-de-France*, the most population-dense region as well the most significant metropolitan of France, more than ten railway tracks have been selected.

There does not exist any particular categorization of the railway track based upon the length of the tracks in SNCF statistical data. For this research work, although, categorization has been introduced to make data representative on length criteria too. For this research, railway tracks have been divided into three categories; (1) Class-A: long tracks (>300 km), (2) Class-B: medium tracks (100-300 km), and (3) Class-C: short tracks (<100 km). There are 7, 20, and 68 number of tracks belonging to Class-A, Class-B, and Class-C, respectively, which were selected in this research work.

## 5.4. Data Analysis

This section merely illustrates the data in terms of various parameters. Table 5.10 presents this analysis in a systematic form. First of all, based on the working principle of the railway, a comparison between selected electrified and non-electrified railway tracks has been given. In terms of the number of tracks, 44 electrified tracks were selected while 51 were non-electrified tracks, but based upon the length of the tracks, a little above 63% of the tracks chosen were electrified. This track chosen amounts to 20% of the total track length of the French railway infrastructure. The contribution of the non-electrical tracks is a little under 37%, which is around one-tenth of the French railway system. Electrical tracks have 4841 bridges with a  $K_{BG}$  of 1.20, while non-electrical tracks have 2313 bridges with  $K_{BG}$  of 1.46. Similarly, 1821 level crossings were recorded for electrified lines as compared to 2046 level crossings for non-electrified lines. The respective value of  $K_{LG}$  for them turned out to be 3.19 and 1.65, respectively.

In terms of operation of the railway, 56 mixed lines while 39 freight lines were selected for data collection. Mixed lines represent a large percentage of 92% as compared to slightly less than 8% of freight lines. Selected mixed lines represent around 29% of the total French railway infrastructure. Mixed lines have 6755 bridges and 3343 level crossings with the  $K_{BG}$  as 1.26 and  $K_{LG}$  as 2.55, respectively. Freight lines, the lesser part of the French railway network, recorded only 399 bridges and 524 level crossings. The respective values of  $K_{BG}$  and  $K_{LG}$  for level crossing came out to be 1.68 and 1.28.

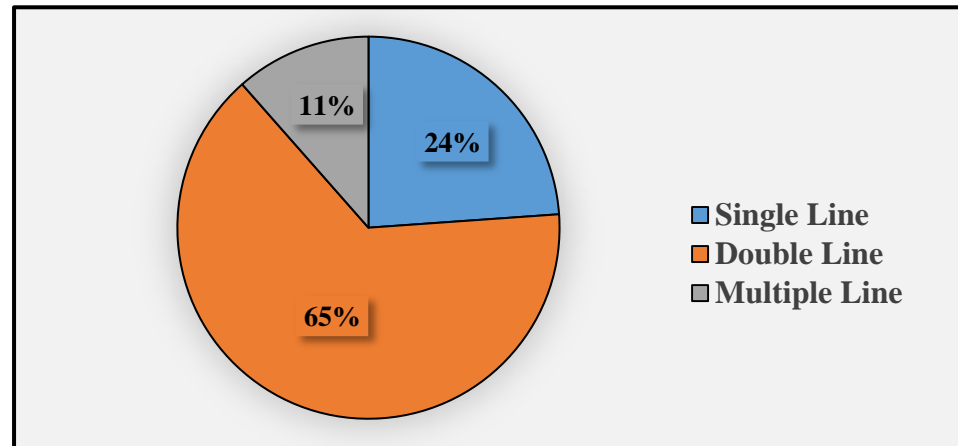
Over-all value of *Kilometer per bridge for Google Earth*,  $K_{BG}$  turns out to be 1.28 that means that throughout the selected railway tracks, after every 1.28 Kilometers, there is a bridge. Similarly, *Kilometer per level crossing for Google Earth*,  $K_{LG}$ , was calculated as 2.37. These two values are vital and will come in handy when in the next section, these two values will be compared with their counterparts for SNCF statistical data as given in Table 4.3, i.e.,  $K_{BS}$  and  $K_{LS}$ . This comparison is done so that the newly developed approach of data collection using Google Earth can be verified.

**Table 5.10. Data Analysis of the Selected Railway Tracks**

<b>Parameter</b>	<b>Criteria</b>	<b>No. of Tracks</b>	<b>Length (km)</b>	<b>Percentage of Selected Sample by Length (%)</b>	<b>Percentage of French Railway Network by Length (%)</b>	<b>No. of Bridges</b>	<b>Kilometer per Bridge for Google Earth (K<sub>BG</sub>)</b>	<b>No. of Level Crossings</b>	<b>Kilometer per Level Crossing for Google Earth (K<sub>LG</sub>)</b>
<b>Working Principle</b>	<b>Electrified</b>	44	5811.1	63.28	20.04	4841	1.20	1821	3.19
	<b>Non-Electrified</b>	51	3371.6	36.72	11.63	2313	1.46	2046	1.65
<b>Operation</b>	<b>Mixed</b>	56	8511.9	92.69	29.35	6755	1.26	3343	2.55
	<b>Freight</b>	39	670.8	7.31	2.31	399	1.68	524	1.28
<b>TOTAL</b>		95	9182.7	100.00	31.66	7154	1.28	3867	2.37

**Table 5.11. Summary of Track (in km) based upon Track Multiplicity**

Track Type	Electrical		Non-Electrical		Total
	Mixed	Freight	Mixed	Freight	
Single Line	373.8	41.8	1319.6	457.7	2192.9
Double Line	4561.7	101	1243.4	28.3	5934.4
Multiple Line	717.3	15.5	296.1	26.5	1055.4
<b>Total</b>	5652.8	158.3	2859.1	512.5	9182.7



**Figure 5.1. A Comparison of tracks based upon *Track Multiplicity***

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Table 5.11 summarizes the Google Earth track data based upon *Track Multiplicity* and *Track Type*. It can be observed that around 6000 km of the selected railway tracks are double line tracks in which there are two rails are running parallel. 2192.9 km of the covered tracks fall into single line track while a little over 1000 km of the tracks are multiple lines in which more than two rails run in parallel. These multiple tracks usually exist near metropolitan cities such as Paris, Strasbourg, Lyon, Lille, etc.

A comparison of the percentage of occurrence of these tracks is presented through a bar chart in Figure 5.1. Around 65% of the selected tracks are double line, while 24% belong to the single line category. Only 11% of the tracks are multiple tracks. A brief comparison of tracks based upon working principle (electricity or no electricity) and operation (mixed trains or freight trains) against track multiplicity has also been presented in Table 5.11.

### **5.5. Method Verification**

One of the main objectives of this research work is to develop a new approach to data collection using Google Earth to compensate for the deficiencies encountered during MFA studies. Using this newly developed method, data for nearly one-third of the French Railway Network was successfully collected using Google Earth. The collected data reasonably allows us to attempt a method verification, if not validation, and comparing it with statistical data of SNCF.

The main idea behind the verification is based upon the occurrence of two infrastructures i.e., bridges and level crossings throughout the French railway system. Railway bridges and level crossings are the most frequently occurring structures in the railway infrastructure. To make the comparison for verification purposes, four parameters i.e.,  $K_{BS}$ ,  $K_{LS}$ ,  $K_{BG}$ , and  $K_{LG}$ , were developed as described in Section 4.2. The aim is to compare  $K_{BS}$  with  $K_{BG}$  and  $K_{LS}$  with  $K_{LG}$  to attempt method verification. Values of  $K_{BS}$  and  $K_{LS}$ , those related to the average distance between bridges and level crossings for SNCF data, have already been given in Table 4.3, which were calculated using Eq. 3 and Eq. 4, respectively. Related parameters ( $K_{BG}$  and  $K_{LG}$ )

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for track data collected from Google Earth for various track types and their averages, as calculated using Eq. 1 and Eq. 2, have also been presented in Table 5.10. In the following Table 5.12, these parameters have been compared, and a brief analysis has been given.

As per Table 5.12, the value of  $K_{BS}$  i.e., *Kilometer per Bridge for SNCF data*, is 1.08 which indicates that, on average, after every 1.08 km, there is a bridge in the French Railway System as calculated using Eq. 3. On the other hand, for the railway data collected from Google Earth in this research work, the corresponding value  $K_{BG}$  turns out to be 1.28. This value signifies that, for the length of the railway for what the data has been collected using Google Earth, after every 1.28 kilometers, on average, there is one bridge. The percentage difference between these two values is approximately 15%.

For the level crossings, *Kilometer per Level Crossing for SNCF data ( $K_{LS}$ )* was calculated as 1.67 using Eq. 4. The corresponding value for Google Earth collected data i.e.,  $K_{LG}$ , turns out to be 2.37. The percentage difference between these two values comes out to be just less than 30%. This difference seems enormous as compared to that of the bridge parameter.

There are several reasons which may explain this ambiguity. Apart from the overall values of these parameters, as presented in Table 5.12, values for these parameters for various scenarios have been summarized in Table 5.13. Based upon the type of tracks, tracks that work on electricity have lower  $K_{BG}$  of 1.20 as compared to those tracks which do not work on electricity, which is 1.46. On the other hand, the value of  $K_{LG}$  for electrified tracks is 3.19 as compared to 1.65 for non-electrified tracks. As per mentioned values and the observation of the railway tracks while collecting data on Google Earth, there are rarely any level crossings on tracks that work on electricity. Such tracks usually cross over the road thorough railway bridges. Hence, values of *Kilometer per Level Crossing ( $K_{LG}$ )* are more significant for tracks operating on electricity. In contrast, values for  $K_{BG}$  are higher, which affects the overall values of  $K_{BG}$  and  $K_{LG}$ . Similar trends have been observed for mixed lines as compared to freight lines as can be seen in Table 5.13.

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Additionally, it can also be seen that independent values of  $K_{LG}$  decrease and become closer or lower than  $K_{LS}$  if calculated neglecting lengths of the tracks covered by High-speed railways (TGV) and Mixed Double Track Electrical lines. The reason behind this deduction is that such type of tracks rarely have any level crossing given their high-speed and priority these are given during their run. Values of  $K_{BG}$  and  $K_{LG}$  will eventually become closer to  $K_{BS}$  and  $K_{LS}$ , respectively, if more length of the data is collected, which was not possible during limited time and resources of this given research work.

Hence, it can be concluded that for the part of the French Railway infrastructure covered in this research, which is just one-third of the whole, these differences are within a reasonably acceptable range. This narrow range suggests that this new method of data collection has a lot of potentials.



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**Table 5.12. A Comparison,  $K_{BG}$  vs  $K_{BS}$  and  $K_{LG}$  vs  $K_{LS}$**

<b>Parameter</b>	<b>Kilometer Per Bridge for Google Earth Data (<math>K_{BG}</math>)</b>	<b>Kilometer per Bridge for SNCF Data (<math>K_{BS}</math>)</b>	<b>Percentage Difference</b> $\frac{K_{BG} - K_{BS}}{K_{BG}} \times 100$	<b>Kilometer per Level Crossing for Google Earth Data (<math>K_{LG}</math>)</b>	<b>Kilometer per Level Crossing for SNCF Data (<math>K_{LS}</math>)</b>	<b>Percentage Difference</b> $\frac{K_{LG} - K_{LS}}{K_{LG}} \times 100$
<b>Value</b>	1.28	1.08	15.63	2.37	1.67	29.53

**Table 5.13. A Comparison of  $K_{BG}$  and  $K_{LG}$  values in various scenarios with General  $K_{BS}$  and  $K_{LS}$  values**

<b>Parameter</b>	<b>Kilometer Per Bridge for Google Earth Data (<math>K_{BG}</math>)</b>	<b>Percentage Difference</b> $\frac{K_{BG} - 1.08}{K_{BG}} \times 100$	<b>Kilometer per Level Crossing for Google Earth Data (<math>K_{LG}</math>)</b>	<b>Percentage Difference</b> $\frac{K_{LG} - 1.67}{K_{LG}} \times 100$
<b>Electrified Lines</b>	1.20	10	3.19	47.64
<b>Non-Electrified Lines</b>	1.46	26.02	1.65	-1.21
<b>Mixed Lines</b>	1.26	14.28	2.55	34.51
<b>Freight Lines</b>	1.68	35.71	1.28	-30.47
<b>Excluding TGV</b>	-	-	2.16	22.69
<b>Excluding TGV and Double Electric</b>	-	-	1.12	-49.11

## 5.6. Material Stock Estimation

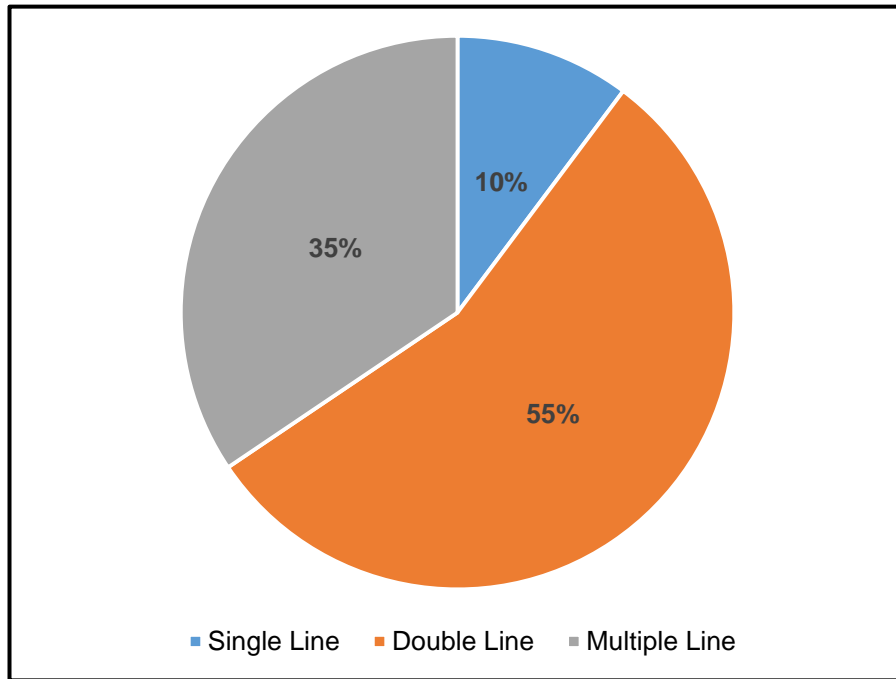
After the establishment of the new method of data collection, the next step is its application for material stock estimation. As explained earlier in Chapter 4, a bottom-up MFA approach has been employed for the estimation purpose in which material intensities of the railway materials have been used. For each material considered in this research, three types of material estimations have been conducted; 1) for part of the French Railway Infrastructure considered in this research, 2) Whole the French Railway network by extending the areal boundary, but assuming same material intensities and 3) Material recovery estimations and future stocks.

### 5.6.1. Steel

Being the metallic component of the railway infrastructure, the amount of steel in the part of the French Railway Infrastructure, which was covered using Goole Earth, has been calculated and given in Table 5.14. As mentioned in Chapter 4, three rails (component of the track) standards have been considered namely, UIC50, UIC54, and UIC60, which correspond to the weight of a rail per meter i.e., 50 kg/m, 54 kg/m, and 60 kg/m. It should be noted that estimations shown in the following table are only for the part of the railway network for what data has been collected using Google Earth. Here, track multiplicity has been considered to estimate the in-use steel stock.

**Table 5.14. Amount of Steel for various track types (kiloton)**

Type	Length of Track (km)	Track Multiplicity	Steel Quantity (Kiloton)		
			UIC50	UIC54	UIC60
Single Line	2192.9	1	235	239	263
Double Line	5934.4	2	1270	1294	1424
Multiple Line	1055.4	7	790	805	887



**Figure 5.2. Comparison of Steel Stock in Single, Double and Multiple Tracks**

Track multiplicity, as explained in Chapter 4, is the number of railway tracks (two parallel lines of rails over which the train runs) on the railway right of way. This parameter is straightforward for single and double lines. Still, for multiple lines, it has been calculated using a weighted average of multiple tracks appearing over the length of the path of the railway line. The double line is the most dominating part of the railway system. Multiple tracks exist for shortest length out of all types of lines but account for more steel quantity as compared to single-line track. This comparison has been manifested in Figure 5.2 for a better graphical explanation.

The total amount of steel stocked in the portion of the French Railway Infrastructure for what data has been gathered through Google Earth has been summarized in Table 5.15. A hefty amount of around 2400 kilotons of steel is stocked in the covered part of French Railway Infrastructure.

The same approach was applied to the whole French Railway Network to estimate the quantity of steel stock in the infrastructure. Table 5.16 presents the steel material stock in

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French Railway Infrastructure for three related rail standards already used. Although the total length of French Railway Network is around 29000 if track multiplicity is taken into account, then the total rail length in the whole French railway infrastructure turns out to be little above 52000 km (NETWORK INVENTORY, 2019). It can be noticed that, on average, the French Railway Infrastructure holds just a little under 6000 kilotons of in-use steel. This data shows that the French railway network is a rich depository of in-use steel.

**Table 5.15. Estimated Steel stock in Covered French Railway Infrastructure (kiloton)**

<b>Standard</b>	<b>Steel Quantity (kt)</b>
UIC50	2295
UIC54	2338
UIC60	2574
<b>AVERAGE</b>	<b>2402</b>

**Table 5.16. Estimated Steel stock in Whole French Railway Infrastructure (kiloton)**

<b>Standard</b>	<b>Steel Quantity (kt)</b>
UIC50	5670
UIC54	5776
UIC60	6359
<b>AVERAGE</b>	<b>5935</b>

### **5.6.2. Wood**

Wood is one of the non-metallic components of any Railway Infrastructure in the form of Railway Sleepers. As explained in Chapter 4, based upon the design of the track and subsequently adopted sleeper density of the railway track amount of wood in the railway infrastructure can be estimated in a stock quantity range.

Table 5.17 presents the wooden stock range calculated in kiloton (kt) for the covered portion of the French railway Infrastructure for three various sleepers densities (SD) i.e., 1340, 1540, and 1660 sleepers per rail length respectively. It is noticeable from the table that more is the sleeper density, more is the quantity of the wood in the railway network. Lower values represent lighter weight sleepers, while higher values represent heavier weight sleepers as mentioned in Table 4.9. It is also clear from the table that double railway tracks hold more

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wooden stock as compared to the single and multiple lines. In total, it has been calculated that the covered portion of the French railway network contains wood in the range from 2104 kt to 3301 kt. The estimated wooden stock has been summarized in Table 5.18.

**Table 5.17. Wooden Stocks in various track types (kiloton)**

Type	Total Length of Track (km)	Track Multiplicity	Wood Quantity (kt)		
			1340	1540	1660
Single Line	2192.9	1	206-322	237-371	254-401
Double Line	5131.9	2	965-1509	1108-1735	1191-1878
Multiple Line	1055.4	7	694-1086	798-1249	857-1352

**Table 5.18. Estimated Wood Stock in Covered French Railway Infrastructure (kiloton)**

Sleeper Density	Estimated Wooden Stock (kt)
1340	1865-2917
1540	2143-3354
1660	2302-3632
<b>Average</b>	<b>2104-3301</b>

Just as steel, wooden material stock for the whole of the French Railway Network has also been estimated. As per statistics, 2814 km of the total French railway network is High-speed rail (Wikiwix, 2020). Therefore, this high-speed portion is considered to have concrete sleepers, but the rest of the length of the French Railway Network has been assumed to have wooden sleepers. Hence, wooden material stock for all of the networks has been given in Table 5.19. It is evident from the table that French Railway Network, just like steel, embodies a considerable amount of in-use wooden stock that ranges from average values of 5020 kilotons to 7878 kilotons.

**Table 5.19. Estimated Wood Stock in Whole French Railway Infrastructure (kiloton)**

Sleeper Density	Estimated Wooden Stock (kt)
1340	4452-6962
1540	5115-8004
1660	5494-8667
<b>Average</b>	<b>5020-7878</b>

**5.6.3. Ballast**

Ballast (also commonly known as crushed stone) is another non-metallic component of the Railway Infrastructure, which is used to provide strong bedding for the railway track. Although the quantity of ballast in the railway network depends upon multiple factors such as density, the height of the track embankment, traffic load, and track geometry for this research work, some simplified and generalized values have been considered, as mentioned in Chapter 4.

Based on material intensities already mentioned, the amount of ballast estimated in the French railway Infrastructure has been given in Table 5.20. These material estimates have been conducted based upon standards of ASCE (American Society of Civil Engineers), namely ASCE60, ASCE41.5, and ASCE30 governed by rail weight per meter. It is again evident that Double line track-type holds most of the ballast followed by multiple line tracks. Single line tracks contribute a minimum quantity of ballast.

**Table 5.20. Ballast Stocks in various track types (kiloton)**

Type	Total Length of Track (km)	Track Multiplicity	Ballast Quantity (Kiloton)		
			ASCE60	ASCE41.5	ASCE30
Single Line	2192.9	1	2125	1419	1000
Double Line	5934.4	2	11501	7679	5412
Multiple Line	1055.4	7	7159	4780	3369

**Table 5.21. Estimated Ballast Stock in Covered French Railway Infrastructure (kiloton)**

Standard	Ballast Quantity (kt)
ASCE60	20785
ASCE41.5	13878
ASCE30	9781
<b>Average</b>	<b>14814</b>

## INPUT DATA INTERPRETATION AND DISCUSSION

It can be seen in Table 5.21 that, on average, a substantial amount of 14814 kilotons of the ballast is present in the covered portion of the French Railway Infrastructure. As far as the whole French Network is concerned, Table 5.22 presents the amount of ballast stocked in the whole railway network of France. It can be noted that French Railway Infrastructure encompasses a gigantic amount of ballast only as track ballast. Based on assumed material intensities, it can be estimated that this infrastructure has more than 36000 kilotons of the ballast, i.e. crushed stone.

**Table 5.22. Estimated Ballast Stock in the Whole French Railway Infrastructure  
(kiloton)**

<b>Standard</b>	<b>Ballast Quantity (kt)</b>
ASCE60	51347
ASCE41.5	34285
ASCE30	24163
<b>Average</b>	<b>36598</b>

### **5.6.4. Concrete**

Concrete is one of the non-metallic components of the Railway Infrastructure, which is partially used under the rails as sleepers. Besides wooden sleepers, which are used for normal speed train tracks, concrete sleepers are also employed in Railway Infrastructure for High-Speed railway tracks. Just like all other materials, based upon track geometry, axel load of the train, and rail traffic intensity, different types of concrete sleepers based upon weight are used.

Using material intensities, as mentioned in Table 4.11, the amount of concrete in the covered portion of the French Railway Infrastructure has been estimated. It should be noted that only High-Speed Rails (LGV) have been considered. A summary of concrete material stock in different railway tracks of the covered portion of the French railway system is given in Table 5.23. It is visible from Table 5.23 that double-track lines contain more concrete in the covered portion of the French railway network.

**Table 5.23. Concrete Stocks in various track types (kiloton)**

Type	Total Length of Track (km)	Track Multiplicity	Concrete Quantity (kt)		
			1340	1540	1660
Single Line	-	1	-	-	-
Double Line	754.5	2	279-1415	321-1627	346-1753
Multiple Line	47.6	7	62-313	71-359	76-387

Table 5.24 gives estimated concrete material stock quantities corresponding to various sleeper densities, as considered in the case of wooden sleepers as well, for the part of French Railway Network for what data has been collected using Google Earth in this research work. Since there exists a vast range of concrete sleepers based upon weight, so, it can be seen in the table that the average of the estimated concrete stock falls in the massive range of 422 kt to 2141 kt.

**Table 5.24. Estimated Concrete Stock in Covered French Railway Infrastructure (kiloton)**

Sleeper Density	Estimated Concrete Stock (kt)
1340	341-1728
1540	392-1986
1660	422-2141
<b>Average</b>	<b>385-1952</b>

**Table 5.25. Estimated Concrete Stock in Whole French Railway Infrastructure (kiloton)**

Sleeper Density	Estimated Concrete Stock (kt)
1340	1041-5279
1540	1199-6067
1660	1289-6540
<b>Average</b>	<b>1176-5962</b>



## INPUT DATA INTERPRETATION AND DISCUSSION

For the whole French Railway Network, it can be noticed in Table 5.25 that, on average, a substantial amount of 1176 kt to 5962 kt of concrete is estimated to be present in the French Railway Infrastructure. It tells that French Railway Infrastructure holds a large sock of the aggregate only as track sleepers.

### **5.6.5. Subgrade Soil**

Railway subgrade layers are on the ground, in cutting or in an embankment. For the construction of new railway lines, it is always desired to make use of the earth material obtained from cuttings on one site to construct an embankment on another site. Almost 97% of the railway tracks in Europe are on embankments, cuttings, or structures (e.g., bridges). It is very critical that the subgrade layer should be made of the appropriate materials and is properly compacted to carry loads of railway traffic. The old practice of use of any old surplus bulk material for filling and insufficient consolidation can still be seen even today on certain railway lines (Trackopedia, 2020; Connor, 2020).

Using material intensities as mentioned in Section 4.5.1.5, the amount of earthen soil utilized in the construction of the part of the French Railway System considered in this research has been estimated. Table 5.26 summarizes these quantities based upon Track Multiplicity. It presents the estimated earthen soil stock within a range. Clearly, double tracks hold the most amount of the subgrade soil followed by Multiple lines track. Similarly, Table 5.27 shows estimated earthen soil stock for the length of the track length considered in this research as well as the whole of the French system.

**Table 5.26. Subgrade Soil Stocks in various track types (gigaton, gt)**

<b>Type</b>	<b>Total Length of Track (km)</b>	<b>Track Multiplicity</b>	<b>Subgrade Soil Quantity (gt)</b>
Single Line	2192.9	1	14-46
Double Line	5934.4	2	77-248
Multiple Line	1055.4	7	48-154

**Table 5.27. Estimated Subgrade Stock in French Railway Infrastructure (gigaton)**

<b>The extent of the Infrastructure</b>	<b>Estimated Subgrade Soil Stock (gt)</b>
Covered in this research	139-448
Whole French Railway Infrastructure	346-1107

### **5.6.6. Bridge Materials**

The French Railway System has an enormous number of bridges that support the railway tracks over the water bodies, roads, other railway lines, or other obstacles. French infrastructure has different types and sized bridges that are different from each other for various reasons e.g., type of bridge, material, length, support conditions, etc. It is very hard to make generalizations in this regard so that material estimation for bridges can be done. Nonetheless, an effort has been made to somehow give a very rough estimate of cement and aggregate in the French Railway Infrastructure, at least in terms of bridges. For this purpose, a number of assumptions and simplifications have been made.

The most abundant type of railway bridge that occurs in the system is that it crosses a road or other similar railway tracks. Most of those bridges are shorter in sizes that range from 25m to 50m. In this research, a single span length of 50m has been assumed based upon the most frequent appearance in the French railway system through observation while collecting data through Google Earth. The width has been assumed to be 25m for the same reason. The height of the deck slab is considered to be around 0.6m, as taken from the literature (Bridges, 2020). The concrete density is such a diverse factor which has a very wide range. Through the literature, it can be assessed that concrete has a density in the range of 1700 kg/m<sup>3</sup> to 2400 kg/m<sup>3</sup> (Jones, 2020). Also, it is found that, in general, concrete is 10-15% cement and 60-75% aggregate. Average values of concrete density, cement content and aggregate percentage have been considered for estimation purposes.

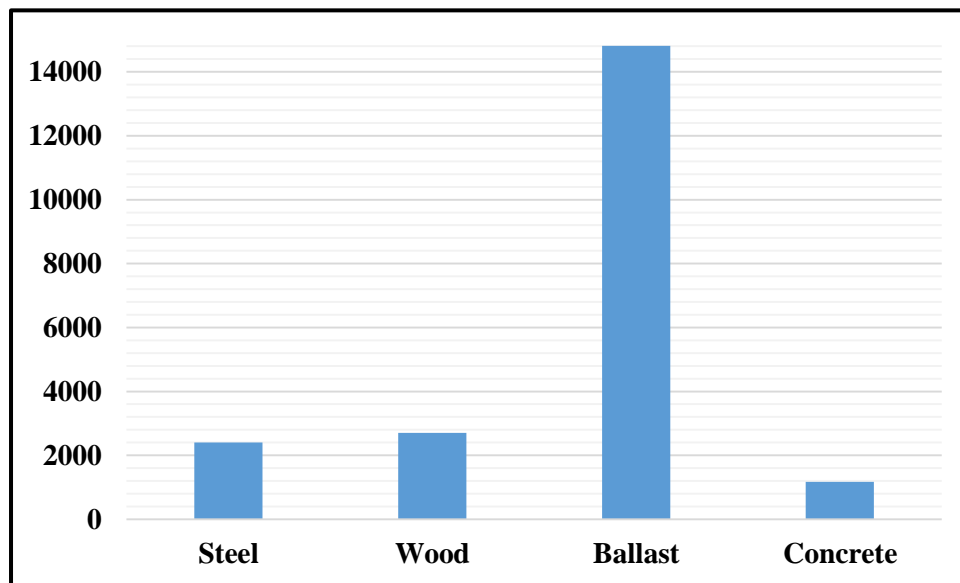
By adopting the above values, concrete, cement, and aggregate quantities have been estimated for a single bridge of 50m length and 25m width. Similarly, the estimation has been extended

to know the in-use stock of concrete, cement, and aggregate in the covered portion of the French railway system and the whole network as well as shown in Table 5.28.

**Table 5.28. Estimated Concrete, Cement and Aggregate Stock (gigaton)**

Extent	Concrete	Cement	Aggregate
One Sample Bridge	1.54	0.19	1.04
Covered Portion of French Railway Network	10999	1375	7425
Whole French Railway Network	41102	5138	27744

Figure 5.3 presents the average stock quantities of four of the basic components of the railway track. Track ballast is by far the most abundant material stock in the covered part of the French railway network. Wooden material is the second most abundant material stock in the covered part of the French Railway Network, although far lesser than the ballast. Steel falls



just behind wood and the concrete, in terms of sleepers, is the least of them all four.

**Figure 5.3. Material Stock Quantities in Covered French Railway Network (in kiloton)**

**5.6.7. Track Maintenance and Future Stocks**

Currently, French Railway Network is struggling between two different infrastructural issues as far as the railway is concerned. On the one hand, the government is all set to launch new projects of High-Speed Railway lines to minimize the travel time and infrastructural upgrade for inter-city trains (Local, 2020; O'SULLIVAN, 2020). On the other hand, more than 9000 km length of small railway lines throughout France are on the verge of obsolescence (EXPLAINED, 2020; JB, 2020).

Whatever the case may be, it means a change in the material stock that needs to be assessed. As of 2019, SNCF is executing more than 1600 projects of the railway track maintenance work, which encompasses 1050 km of the track length throughout France (Reseau, 2020). Maintenance work usually includes replacement of main working components of the infrastructure. Assuming that the subgrade layer is very unlikely to be replaced, an estimation of potential replacement of track material has been conducted. Table 5.29, based upon material intensities as described in Chapter 4, summarizes average material quantities of four main components of the railway infrastructure for this up-gradation. Although it is entirely unclear that what is the duration of these projects, but according to available information, it is assumed that it is the annual up-gradation of the French Railway Network i.e., every year more than 1000 km network is upgraded, and the stock material is replaced. High-Speed Lines have not been considered.

**Table 5.29. Estimated Steel, Wood and Ballast Stock Potential Replacement and Maintenance (kiloton)**

<b>Material</b>	<b>Quantity</b>
Steel	118
Wood	143
Ballast	726

## INPUT DATA INTERPRETATION AND DISCUSSION

Recently, as mentioned before, an issue of near-loss of more than 9000 km of railway tracks situated in rural areas of France has come to limelight. There are arguments that the expansion of High-Speed Rails across France has come at the cost of these neglected *petites lignes* (small lines). In the scenario that these lines are completely neglected, a huge in-use material stock will convert into dead stock. An estimation of the material stock for these lines is presented in Table 5.30. In the other case, the maintenance or up-gradation of these tracks might need additional material resources that might add-up the existing in-use material stock. It should be noted that these projects, if approved, are planned to be executed during the next ten years.

**Table 5.30. Potential Material Stock Replacement or Conversation to Hibernating Stock  
(kiloton)**

<b>Material</b>	<b>Quantity</b>
Steel	1008
Wood	1224
Ballast	6219

## **CHAPTER 6**

# **CONCLUSION**

Throughout previous chapters, a basic understanding of the intended research work and required familiarity of the literature review of the topic have been well established, which ultimately lead to the methodological framework and development of the proposed solution of the problem. Once the interpretation of the input data and results representation has been made, it is now possible to confer upon the conclusion of this research work.

This chapter explores the conclusion of this research work. After the conclusion section, limitations of this research work have also been given, followed by the recommendations on future works that may be conducted based upon the knowledge and method that has been established in this work of research.

## **6.1. Conclusion**

### ***6.1.1. The utility of the Material Flow Analysis (MFA) in Stock Estimation***

MFA is a competent and versatile tool for systematic assessment of material flows and stocks that provides a firm ground for stock estimation of various materials within different systems and infrastructure for a diverse range of time boundaries. It has a high potential of assisting in preparing an inventory of materials stocks for ever-increasing anthroposphere. The applicability and utility of MFA is afflicted by the data deficiencies resulted due to numerous reasons. These reasons are lack of data at the regional level, the unreliability of data in developing countries, uncertainties in available data and unavailability of the input data at all. By eliminating these data issues, MFA can be made more applicable in most of the studies.

### ***6.1.2. Addressing MFA Data Deficiencies through Secondary Tools***

Data issues that are encountered while conducting MFA can effectively be eliminated or reduced. Attempts have already been made to address them by the use of secondary tools and programs such as Geographic Information System (GIS) or Nighttime Light Sattelite Imagery. There is a lot of potential in combining such tools with MFA for eliminating data deficiencies in MFA.

### ***6.1.3. Employment of Google Earth for Data Collection***

Google earth is one such capable tool that can be profitably combined with MFA for the collection of the data. It is a very advanced yet user-friendly and simple-to-use program that allows the user to collect ground data with good precision. Especially for transportation infrastructures, it offers a good opportunity to collect direct data that might not be available in statistical records. It has features that allow its user to track and collect realtime information related to infrastructural products such as lengths of railway lines or road, bridges, tunnels, and other geological features, which can then be converted into useful data. This data can

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further be used for the estimation of the material stocks in the concerned system or infrastructure.

### ***6.1.4. French Railway Infrastructure as a Rich Source of In-use Material Stocks***

The French Railway Infrastructure holds a vast quantity of metals such as Steel and non-metals such as wood, concrete, aggregate, and earthen material. Based upon data collected for one-third of the French Railway Network by the length of the tracks, it can be concluded that this system carries, on average, 14814 kilotons of aggregate (crushed stone), 2274 to 3567 kilotons of wooden materials and 2402 kiloton of steel. Hence, it is essential to maintain the inventory of the materials stock in the urban infrastructures.

## **6.2. Limitations**

This research work has been conducted with the best of efforts and by observing good and honest practices pertaining to the scientific studies. Despite all the efforts and available resources, like other research works, there were a few limitations while doing this research. Those limitations are specified below:

1. Due to time and financial resources stipulations, it was impossible to cover the whole French Railway Network for data collection through Google Earth. Hence, one-third of the total French Railway Network by length has been included, and the proposed method was applied to that. Through the use of scientific justifications, assumptions, and inference, the proposed method has been attempted to be justified.
2. Data collected through Google Earth may appear to struggle as compared to actual on-ground data given the fact that it is an all-out human effort. Data extraction for such a large portion of the complex system is a very tedious and cumbersome job. There were a very few portions of the map which were efficiently available on Google Earth due to weather affected imagery on the program (for example, clouds over a particular



area), map distortion due to pixel problems or in very rare cases, failure to locate parts of railway track on the Google Earth corresponding to the actual one on SNCF map.

3. There have been cases of simplification of data as well as calculations in the research work. As far as the map itself is concerned, while calculating track multiplicity, the weighted average has been considered to have one single and generalized value so that calculation can be made accessible. Similarly, exact material intensities for a given rail line in French Railway System were most of the time were not available. To counter that, available and most suited values from the literature have been taken for stock estimation.
4. There are some other components of Railway Infrastructure which have not been taken in to account during this research work e.g. Railway Stations and electrification systems. Railway Stations are a source of various metallic and non-metallic construction materials. Railway stations in French Railway Infrastructure vary in terms of size, type and operation, hence, it was not feasible to generalize them. Therefore, material estimation for Railway Stations has been left out for this research work. Similarly, as far as electrification system is concerned, it consists of various sub-components itself i.e. overhead lines, signalling boxes, poles, towers and other auxiliary equipment. These components are a rich source of metallic and non-metallic materials but the estimation process for them was very complexed. It was not easy at all to generalize them for the sake of material stock estimation and, hence, those were also left out for the sake of simplification of the estimation work.

### **6.3. Future Recommendations**

This research topic is still very immature, and up to this stage, the proposed method has only been verified based upon the maximum available information. The results are fair and pave the way for some future research works which may explore and broaden this research topic. Some of the future recommendations are given below:

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1. As mentioned earlier, this method has only been verified. For the sake of method validation, this method should be applied to a region for what data is available, and material stock inventory is documented so that the results of this method can be compared with those once applied. For example, it is possible to apply this method on the whole Paris Region (Île-de-France) for data collection and material stock estimation (e.g., Steel) and then comparing it with already documented statistical data for the same region.
2. This method can be used in other urban infrastructure systems, such as buildings, highways, airports and waterways.
3. This method can also be applied to other developed countries for what statistical data is well recorded so that the applicability of the method may be tested. And once the method is established, it can then be used to collect data for developing or underdeveloped countries as well.
4. Until now, the data has been manually collected through human effort. Knowing the fact that Artificial Intelligence, Machine Learning, and Big Data are the most flourishing fields in the World right now, those can be very helpful in transforming data collection from manual to computer-aided programs where machines do the collection part.
5. To eradicate the deficiency of Google Earth data availability in underdeveloped and developing countries, remote sensing and other innovative programs can be arranged for up-gradation of the maps in those areas. For example, installing image collection sensors on transportation vehicles (trucks, trains, etc.) can effectively help in that.

## **CHAPTER 7**

# **EXTENDED ABSTRACT**

## **(IN FRENCH)**

La population humaine est en constante augmentation entraînant une croissance économique. Depuis le début du XXe siècle, les infrastructures urbaines nécessaires sont de plus en plus importantes pour faire fonctionner la société et l'économie. Elles consomment, à leur tour, de nombreuses ressources naturelles limitées. Cette limite oblige l'humanité à concevoir de nouvelles politiques d'extraction, de production, d'utilisation, de recyclage, de réutilisation et d'élimination des matériaux. Ces matériaux sont utilisés pour les infrastructures urbaines et génèrent des déchets en tant que sortie du système. Le matériau qui est stocké dans l'infrastructure devient stock. Certains outils et méthodes sont utilisés pour l'évaluation du bilan matières afin de prendre des décisions politiques pour contrôler les intrants, les extrants et les stocks. L'analyse des flux de matériaux (AFM) est l'un des outils utilisés à l'échelle mondiale. Outre les nombreux atouts et avantages de l'AFM, il présente également certains désavantages qui ont été explorés dans le cadre de ces travaux de recherche, et une solution a également été proposée.

## **7.1. Perspective mondiale de l'infrastructure moderne et de la comptabilité des matières**

Le XXème siècle a vu une augmentation sans précédent de la population à travers le monde. Au cours des cents dernières années, la population humaine a augmenté quatre fois par rapport à ce qu'elle était au début du XXe siècle (Krausmann et al., 2009). Actuellement, la population mondiale s'élève à 7,7 milliards d'habitants, et elle devrait être d'environ 8,5 milliards en 2030, 9,7 milliards en 2050 et 10,9 milliards en 2100 (Nations Unies, 2019; Pison, 2019). De même, la croissance économique mondiale a également été multipliée par 20 au cours du siècle dernier (Swilling, 2011; Maddison, 2007). Cette expansion démographique et cette énorme croissance économique mondiale ont favorisé l'urbanisation, et les petites villes ont commencé à croître vers l'extérieur. Les villes se développent de manière très complexe en fonction de la taille, des politiques économiques, politiques et des structures sociales (Kennedy et al., 2007).

Pour accueillir une population sans cesse croissante dans l'espace relativement restreint des villes, il fallait développer des systèmes d'infrastructure vastes et efficaces qui pourraient soutenir les sociétés actuelle et future. Le développement de systèmes d'infrastructure substantiels comprenait des bâtiments, des routes, des voies ferrées, des ports, des voies aériennes, des communications et d'autres réseaux et structures auxiliaires qui sont un besoin fondamental pour qu'une société fonctionne. Cette énorme construction d'infrastructures a donné naissance à une nouvelle ère du monde appelée Anthropocène (Lucy, 2019). Le terme anthropocène est une proposition d'inscription pour une nouvelle ère géologique terrestre. Il comprend la période au cours de laquelle l'homme est devenu l'un des facteurs d'influence les plus importants sur les processus biologiques, géologiques et atmosphériques sur terre. Cette nouvelle ère a ajouté une autre sphère dans l'atmosphère terrestre appelée Anthroposphère. L'anthroposphère (parfois également appelée technosphère) est la partie de l'environnement créée ou modifiée par les humains pour être utilisée dans les activités humaines et les habitats humains (janvier 2019).

Il y a environ 50 ans, en 1965, Abel Wolman a inventé le terme de métabolisme urbain et a lancé un concept révolutionnaire dans lequel il comparait une ville à un organisme vivant. Il a soutenu que tout, comme un organisme vivant a des entrées, des sorties et des stocks de matériaux et d'énergie, une ville peut avoir son métabolisme. Il a appliqué ce concept à une ville américaine hypothétique d'un million d'habitants et a estimé les flux d'énergie, d'eau, de matériaux et de déchets entrants et sortants de cette ville (Wolman, 1965; Kennedy, 2007).

À l'heure actuelle, il existe plusieurs méthodologies qui peuvent être appliquées pour décrire le processus métabolique des villes, des régions et des nations. L'une de ces méthodes est l'analyse des flux de matériaux (AFM), qui a été appliquée avec succès dans la gestion des ressources, la gestion des déchets, la gestion de l'environnement et d'autres domaines similaires (Brunner et Rechberger, 2016).

## **7.2. L'infrastructure**

La Société Américaine des Ingénieurs Civils (ASCE) définit l'infrastructure comme:

«L'infrastructure qui soutient les activités humaines comprend des systèmes physiques, sociaux, écologiques, économiques et technologiques complexes et interdépendants tels que le transport et la production et la distribution d'énergie; gestion des ressources en eau; la gestion des déchets; des installations soutenant les communautés urbaines et rurales; les communications; développement durable des ressources; et la protection de l'environnement.  
"»

Les actifs d'infrastructure sont des structures physiques, des installations et des réseaux qui fournissent des services essentiels au public. Ces actifs comprennent les structures de transport (routes, ponts, tunnels, voies ferrées, aéroports et ports maritimes), les sociétés d'énergie et de services publics, les entités de communication et les services sociaux tels que les établissements d'enseignement et les hôpitaux (Dawson, 2013).

### **7.3. Infrastructure urbaine**

L'infrastructure urbaine est une notion polyvalente qui dépasse un ensemble de systèmes, d'installations et de services publics conçus. Il est également lié aux systèmes de gouvernance mondiaux et locaux, aux problèmes connexes de croissance économique, de changement climatique et de déchets municipaux (Ferrer, 2018). Il s'agit d'un cadre interne d'une ville par rapport au support structurel sous-jacent du bâtiment. Les populations et les civilisations modernes deviennent de plus en plus tributaires des systèmes d'infrastructures urbaines pour fournir des services essentiels qui soutiennent la prospérité économique dans la croissance et la qualité de vie (Ouyang, 2012 ).

### **7.4. Métabolisme urbain**

Un corps humain a besoin de nourriture comme intrant afin que le corps puisse convertir cette nourriture en énergie pour exécuter les processus cellulaires dans le corps et pour former des blocs de construction tels que des protéines, des lipides et autres. De même, les besoins métaboliques d'une ville peuvent être décrits comme l'ensemble de l'énergie et des matériaux dont la ville et ses habitants ont besoin pour les aider à maintenir et faire fonctionner correctement le système de la ville.

Abel Wolman, en 1965, a inventé le terme de métabolisme des villes dans lequel il a expliqué que le métabolisme d'une ville est analogue à celui d'un corps humain. Il a appliqué ce concept à une ville américaine hypothétique d'un million d'habitants et a estimé les flux d'énergie, d'eau, de matériaux et de déchets entrants et sortants de cette ville (Wolman, 1965; Kennedy, 2007). Semblable au processus physique chez les animaux, les arbres et les forêts, le métabolisme de l'Anthroposphère comprend l'absorption, le transport et le stockage de toutes les substances, la transformation biochimique au sein de l'Anthroposphère et la qualité et la quantité de tous les sous-produits comme le gaz, les conduits de fumée, les déchets et les eaux usées (Baccini, 1991).

## **7.5. Analyse des flux de matières (AFM)**

L'analyse des flux de matières (AFM) est un outil permettant d'évaluer systématiquement les flux de matières et les stocks dans des limites temporelles et spatiales spécifiques au sein d'un système prédéfini. Il est utilisé pour décrire, évaluer et étudier le métabolisme des processus anthropiques. Les résultats de l'AFM peuvent facilement être contrôlés par une simple équation de bilan massique régie par la loi de conservation de la matière dans laquelle tous les intrants, extrants et stocks d'un système sont comparés. Il s'agit d'un lien entre les sources, leurs voies et leurs éliminations, qui fait référence au débit de la chaîne de processus qui comprend l'extraction, la fabrication, la consommation, le recyclage et, enfin, l'élimination des matériaux (Bringezu, 2018; Brunner, 2003).

L'AFM fournit une vue de l'analyse du système des différents flux et processus interconnectés pour soutenir la conception stratégique et prioritaire des mesures de gestion. Il s'agit d'un outil indispensable pour opérationnaliser le concept de durabilité et promouvoir une planification et une gestion des ressources naturelles efficaces. De plus, c'est un outil puissant pour soutenir la prise de décision politique dans les domaines de la gestion des ressources et de l'environnement. En matière de politique, l'AFM peut être utilisée pour la reconnaissance précoce, la définition des priorités pour analyser et améliorer l'efficacité des mesures et pour concevoir des stratégies de gestion des matériaux efficaces compte tenu de la durabilité (Bringezu, 2018; Barrett, 2002; Hendriks, 2000).

## **7.6. Analyse des flux de matières (AFM) et son application dans l'estimation des stocks et des flux**

L'analyse des flux de matières (AFM) est un outil utile pour évaluer systématiquement les flux et les stocks d'un matériau donnés à l'intérieur de certaines limites géographiques et temporelles du système. Dans les domaines de la gestion des ressources, de la gestion des déchets et de la gestion de l'environnement, cette méthode est très bénéfique pour estimer le

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flux de matériaux et évaluer l'efficacité des matériaux (Takahiro et al., 2009; Brunner & Rechberger, 2016). Les études de l'AFM ont trois objectifs principaux: 1) identifier les flux de matières et les stocks, 2) contextualiser et interpréter les flux et les stocks, et 3) recommander des politiques pertinentes pour une utilisation optimale des ressources (Hendriks et al., 2000).

Dans l'AFM, il existe principalement deux approches; 1) Approche descendante, 2) Approche ascendante. L'approche descendante utilise des données statistiques de séries chronologiques annuelles pour la production de matériaux afin d'estimer les stocks de matériaux, tandis que l'approche ascendante quantifie le nombre de produits à l'intérieur de la frontière spécifique puis les intensités matérielles de ces produits sont multipliées par le nombre de produits pour estimer les stocks de matières (Takahiro, 2009; Paul, 2004).

De nombreuses études ont déjà été menées pour déterminer les flux de divers matériaux, par ex. cuivre, argent, chrome, fer, plomb, acier, nickel et aluminium aux États-Unis, en Europe et au Japon (Kazue, 2009). De nombreuses études ont été menées sur les infrastructures de construction et de transport pour la détermination des stocks présents dans la sphère anthropique. Au sein des infrastructures de transport, l'infrastructure routière a été étudiée par de nombreuses études aux États-Unis et en Europe (Wiedenhofer, 2015; Miatto, 2017).

### **7.7. Problèmes de données dans AFM**

#### ***7.7.1. Lacunes dans les données au niveau régional***

L'AFM est un outil qui aide les décideurs à comprendre le processus du métabolisme urbain pour différentes gammes spatiales puisqu'il permet aux activités et processus régionaux tels que la construction, le transport, la consommation et l'élimination d'être systématiquement liés aux intrants et extrants des systèmes urbains. Il a donc un grand potentiel pour être utilisé comme outil d'orientation au niveau régional (Hendriks, 2000 ). Des approches ascendantes et descendantes de flux de matières ont été appliquées dans de nombreuses études pour obtenir des résultats satisfaisants. Dans une approche descendante, la consommation historique de



matériaux dans diverses infrastructures et leur durée de vie correspondante est utilisée pour estimer les stocks de matériaux. Cependant, cette approche est pratiquement limitée à une échelle nationale ou mondiale en raison de lacunes dans les données et n'a pas de résolution spatiale. Ce problème se pose en raison du manque de données commerciales ou de données de consommation au niveau régional. Ainsi, l'estimation des stocks peut également être un défi pour les produits à longue durée de vie, comme les bâtiments et les infrastructures. Cette estimation peut être effectuée par une approche ascendante dans laquelle tous les biens pertinents dans une frontière spatiale (comme une ville ou une région) et leurs intensités matérielles correspondantes sont quantifiés puis agrégés. Cependant, ces approches nécessitent beaucoup de travail et dépendent fortement des données statistiques. De plus, très peu d'études de cas sont disponibles pour les villes et les pays. (Bailang, 2018). Il est nécessaire de reconstruire les données de l'AFM pour diverses gammes spatiales, y compris à l'échelle régionale. L'un des obstacles empêchant de construire de telles données à différentes échelles géographiques s'avère coûteux en temps et en efforts (Courtonne, 2015). C'est parce que les données régionales qui sont en quelque sorte disponibles sont généralement non structurées, interdisciplinaires, de formats et de qualités différents, et proviennent de sources hétérogènes. Ces sources peuvent inclure des tableaux commerciaux officiels, des mesures scientifiques, des modèles, des industries ou des associations. Cela donne à penser que les bases de données des AFM régionales sont généralement très hétérogènes. D'autre part, parfois, les données de l'AFM ne sont pas basées sur des ensembles de données empiriquement bien fondées, mais sur des valeurs individuelles et isolées, qui ne sont pas toujours fournies dans des formats cohérents. La base d'information disponible est souvent considérablement limitée (Schwab et al., 2017).

Selon Tachibana (2008), l'AFM est un outil essentiel pour avoir une vision claire de la structure de la société régionale et obtenir des indicateurs de l'environnement. Habituellement, les communautés régionales sont liées aux gouvernements locaux. Par conséquent, le rôle de l'information dans l'élaboration des politiques pour les gouvernements locaux a gagné en importance. Cependant, le rôle de l'AFM ne s'est pas tellement propagé à l'échelle du

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gouvernement local en raison du manque de données statistiques locales, et les méthodologies de l'AFM pour le calcul des indicateurs environnementaux au niveau régional n'ont pas encore été établies. D'une manière générale, les études sur les indicateurs environnementaux sont dirigées à l'échelle nationale et, malheureusement, très peu d'études ont été menées au niveau régional.

### ***7.7.2. Manque de disponibilité des données pour les pays en développement et sous-développés***

Les données qui soutiennent les études de l'AFM sont principalement disponibles pour les pays développés. L'Union européenne (UE) et d'autres pays développés ont documenté un niveau de données suffisant pour mener à bien l'AFM et ont déjà intégré celles-ci en tant que composantes centrale de la comptabilité environnementale pour fournir une politique et une prise de décision fondées sur des preuves (Vilaysouk et al.2017). Par exemple, la Sound Material Cycle Society au Japon a appliqué trois indicateurs pour atteindre les objectifs politiques de haut niveau social, qui sont dérivés de l'AFM. La Commission européenne a mis au point un tableau de bord de l'efficacité des ressources pour suivre les progrès vers une efficacité accrue des ressources dans les États membres. Les pays du G7 ont conçu une nouvelle initiative pour intégrer la gestion des ressources et la politique économique dans un seul cadre.

Au contraire, dans les pays en développement où les statistiques de données publiques ne sont pas bien organisées ou moins fréquemment disponibles, les données relatives aux stocks en usage sont très difficiles à trouver (Kazue, 2009). Les pays en développement comme la Chine, la Russie et l'Inde disposent d'un stock important d'acier dont ils ne disposent pas de données statistiques disponibles (Feng-Chi, 2011). Pour la mise en œuvre et le suivi des progrès des objectifs de développement durable, la productivité, la gestion et l'efficacité des ressources soient mentionnées comme des besoins essentiels pour les pays en développement afin d'assurer la fourniture de ressources naturelles en temps opportun et à un prix abordable.

Cependant, Baninla et al. (2018) soutiennent que la productivité minérale est faible en Afrique et dans les pays en développement asiatiques par rapport aux pays développés.

Par opposition aux besoins d'informations critiques, les pays en développement manquent également de capacités institutionnelles, de ressources financières et de capital humain pour la communication des statistiques. D'une part, les pays en développement ont besoin de techniques de collecte d'informations adaptées à leurs capacités et ressources limitées; d'autre part, des systèmes de suivi et de documentation doivent être mis en place. Par exemple, de nombreuses études s'appliquent aux bases de données internationales. Pourtant, ceux-ci ne semblent pas entièrement pertinents pour les caractéristiques socio-économiques des pays en développement telles que les activités économiques informelles, les différents systèmes industriels et la tendance à la sous-déclaration (Vilaysouk et al.2017).

### ***7.7.3. Incertitudes de données dans MFA***

Les incertitudes liées aux données dans l'AFM, comme dans d'autres outils d'analyse des systèmes environnementaux, comme l'ACV, sont très souvent de niveau variable. Quelques études montrent qu'une grande partie des données utilisées dans les études sur l'AFM sont de faible qualité et à forte incertitude. Étant donné l'intention d'utiliser l'AFM dans la comptabilité environnementale, et en particulier comme outil de politique et de gestion environnementales, il est évident que des données plus fiables doivent être collectées (Danius, 2001).

La connaissance de l'exactitude des données sur le fait que certains ensembles de données sont fiables et représentatifs permet aux utilisateurs des résultats calculés d'évaluer la fiabilité et la représentativité des résultats. L'un des aspects les plus importants de l'AFM est de s'assurer que les incertitudes sont réduites au minimum, mais en ce qui concerne les résultats, il faut noter que les incertitudes sont inhérentes à l'AFM. De plus, les ensembles de données statistiques disponibles ne répondent pas suffisamment aux exigences de données spécifiées en termes d'exhaustivité et de niveau de différenciation. Pour les besoins de l'analyse, les

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données manquantes doivent donc être générées par une combinaison de sources multiples, d'estimations, d'avis d'experts et de modèles, ce qui conduit à un certain degré d'incertitude dans les données de l'AFM (Schiller, 2017).

Schwab et al. (2017) ont fait valoir que dans les études de l'AFM, les informations disponibles sont essentielles pour la validité et peuvent varier d'une étude à l'autre en fonction du type de matériau et de la portée de l'étude. Mais il convient également de garder à l'esprit que les études d'AFM avec des limites précises des systèmes spatial et temporel présentent des incertitudes de données en raison de connaissances limitées. Cette incertitude survient parce que, pour chaque flux particulier, il n'y a qu'une seule valeur correcte, qui n'est probablement pas connue avec une certitude absolue. Ainsi, les résultats des études de l'AFM sont étroitement liés à la qualité des données appliquées, qui fait référence au degré de crédibilité perçu des données fournies.

Dans une étude de Laner (2015) sur l'incertitude des données d'entrée de l'AFM pour les flux de plastique en Autriche, ils ont fait valoir que les flux de matières sont spécifiques à une certaine région géographique, à une certaine période et au matériau. Pour cette raison, il existe un certain manque d'informations sur la saisie des données de l'AFM, quel que soit le niveau de sophistication adopté dans l'approche. Les données appropriées pour le système étudié peuvent souvent ne pas être disponibles. Par conséquent, les données correspondant au système proposé sont dérivées de l'augmentation et de la réduction d'échelle en utilisant la transformation des données rapportées pour d'autres systèmes similaires, ou en utilisant un jugement d'expert.

### ***7.7.4. Problèmes liés à la collecte des données d'entrée***

Patricio (2015) montre comment l'entrée de la collecte de données affecte les résultats de l'AFM. Concernant l'utilisation des données chronologiques de l'AFM pour 1996-2011 à trois niveaux spatiaux, à savoir national (Suède); régional (région de Stockholm) et métropolitain (Stockholm, Göteborg et Malmö), il a été décrit comment la qualité des données d'entrée et

les erreurs dans les données d'entrée affectent les résultats globaux. Il conclut que lorsque le niveau spatial diminue du niveau national au niveau régional et métropolitain, la disponibilité des données diminue également.

L'acquisition de données pour la réalisation de l'AFM est compliquée et est donc étendue pour inclure des sources informelles, y compris à des études de marché, aux jugements d'experts, aux meilleurs scénarios et à d'autres connaissances pratiques (Rahman et Kim, 2019). En outre, au-delà des bases de données statistiques nationales et internationales, des techniques de collecte de données secondaires et complémentaires ont été récemment utilisées dans différentes études (Bailang et al. 2018).

## **7.8. Utilisation de méthodes secondaires pour compléter les problèmes de données dans AFM**

Certaines méthodes et outils secondaires, comme l'AFM, doivent être utilisés pour une meilleure estimation et compréhension des stocks et des flux afin de surmonter les problèmes de données qui surviennent en raison de la disponibilité limitée ou inexistante de données statistiques compilées à diverses échelles spatiales (nationales, régionales ou mondiale), les incertitudes dans les données de l'AFM et le manque de données disponibles pour les pays en développement et sous-développés. Quelques études ont été menées dans lesquelles des méthodes secondaires telles que les programmes d'imagerie par satellite, le système d'information géographique (SIG), la lumière nocturne et la télédétection ont été utilisées pour combler le manque de données dans l'estimation des stocks et des flux. Dans les sections suivantes, ces méthodes sont brièvement décrites et quelques études utilisant pour remédier aux carences de l'AFM sont présentées.

### **7.8.1. *Système d'information géographique***

Un système d'information géographique (SIG) est un système conçu pour capturer, stocker, manipuler, analyser, gérer et présenter des données géographiques et spatiales. Il fait référence à diverses technologies, processus, techniques et méthodes, qui sont liées à

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différentes opérations et ont de nombreuses applications en ingénierie, planification, gestion, logistique, assurance, télécommunications et affaires. Les applications SIG sont des outils qui permettent aux utilisateurs d'analyser des informations liées à l'espace, d'éditer des données cartographiques et de présenter les résultats de toutes ces opérations (Clarke, 1986; Maliene, 2011).

Tanikawa et Hashimoto (2009) ont souligné que l'application d'approches AFM de haut en bas et de bas en haut utilisant des données spatiales et temporelles pour estimer le stock de matériaux est utilisée depuis longtemps. De telles études sont cependant non seulement insuffisantes pour l'élaboration des politiques au niveau régional mais aussi pour la localisation géographique des stocks. L'évaluation du métabolisme urbain dans les infrastructures urbaines est nécessaire pour comprendre les changements dans l'accumulation de stock de matériaux. Une énorme quantité de matériaux de construction est nécessaire pour le développement de telles infrastructures engendrant un nouveau flux de déchets. Ils ont fait valoir que les estimations aux niveaux national et régional des flux de matières et des stocks sur la base des données statistiques disponibles sont utiles pour évaluer les entrées, les sorties et l'accumulation de matières sur une période de temps mais ne sont pas en mesure de donner leur distribution spatiale respective aux décideurs. Pour y parvenir, ils ont proposé un modèle ascendant du Système d'information Géographique à 4 dimensions (4d-GIS) dans lequel ils ont fusionné les anciennes cartes SIG d'urbanisme disponibles du Japon avec les dernières cartes numérisées qu'ils ont préparées pour des parties des deux villes cibles. Ce modèle leur a permis d'obtenir des informations supplémentaires tels un certain nombre d'étages, l'utilisation des bâtiments, la largeur des routes et des informations sur le sol ou la surface. Ils ont appliqué ce modèle aux petites zones de 8 km<sup>2</sup> et 11 km<sup>2</sup> de Manchester au Royaume-Uni et de Wakayama au Japon, respectivement, pour déterminer les stocks de matériaux dans les bâtiments, les routes et les chemins de fer ainsi que leur distribution spatiale.

Fritz (2016) a étendu cette approche à l'ensemble du niveau de la ville et a appliqué un modèle similaire à la ville de Vienne, en Autriche, en utilisant des données statistiques ainsi

que des données SIG de diverses autorités municipales pour estimer le stock de matériaux dans les infrastructures du bâtiment. Dans leur recherche, ils ont souligné le manque de localisation détaillée des stocks de matériaux tout en considérant uniquement les données statistiques. L'utilisation du SIG corrige cette carence. Des études antérieures qui utilisaient le SIG en combinaison avec des données statistiques ont eu des problèmes pour combiner différents ensembles de données SIG (par exemple, combiner un ensemble de données spatiales avec un ensemble de données temporelles). Ils ont proposé une meilleure approche pour fusionner différents ensembles de données SIG concernant les types de structure des bâtiments et les stocks de matériaux. Il existe de nombreuses incertitudes dans l'approche en raison de la collecte de données lors d'une enquête, du manque de documents, de la documentation limitée, des plans de construction obsolètes et des bâtiments démolis.

Tanikawa et al. (2015) ont en outre proposé un modèle ascendant pour estimer le stock de matériaux de construction en service dans les infrastructures urbaines de 47 préfectures du Japon à l'aide du SIG. La portée de cette étude comprend les bâtiments, les routes, les voies ferrées, les réseaux d'eau souterrains, les aéroports, les ports maritimes et les barrages. En fonction du type de structure, différentes méthodes de calcul et sources de données ont été utilisées. Pour les bâtiments, deux types d'ensembles de données ont été utilisés pour deux plages temporelles différentes. L'un d'eux était un ensemble de données SIG compilé par l'éditeur de cartes commerciales du Japon et l'autre a été créé à l'aide de données statistiques sur l'espace au sol du Ministère des terres, des infrastructures, des transports et du tourisme.

Pour les routes, des données SIG à l'échelle du pays et des données statistiques au niveau de la préfecture ont été utilisées pour obtenir la classification, la longueur et la largeur des routes. Alors que pour les chemins de fer, seules les données SIG ont été prises en compte, pour les réseaux de canalisations souterraines, seules les données statistiques préfectorales étaient disponibles. Les ensembles de données pour d'autres structures étaient similaires aux données ferroviaires. Enfin, pour toutes les structures, les intensités des matériaux ont été multipliées

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par plusieurs produits pour chaque type de structure, comme norme dans une approche ascendante, pour estimer le stock de matériaux.

### ***7.8.2. Imagerie satellite de lumière nocturne***

L'imagerie satellite de lumière nocturne (NTL) est le produit mondial d'éclairage nocturne observé par satellite qui est devenu l'un des outils de collecte de données géospatiales les plus utilisés. Ces produits montrent les emplacements où l'éclairage artificiel est présent et une mesure de la luminosité observée depuis l'espace, comme le montre la figure 2.1 (Elvidge, 2017). Depuis la fin des années 1990, l'imagerie satellite Nighttime Lights est devenue un outil efficace pour relier des paramètres socio-économiques tels que l'urbanisation, l'activité économique et la population. Des recherches récentes montrent que les données d'imagerie NTL nouvelles et améliorées peuvent servir de moyen fiable pour l'analyse dynamique de ces variables, qu'elles augmentent ou diminuent avec le temps. En particulier, les données d'imagerie NTL deviennent plus pertinentes pour détecter, estimer et surveiller les facteurs socio-économiques dans les pays et les régions infranationales où des données statistiques officielles fiables peuvent faire défaut (Bennett et al., 2017). Les avantages de l'imagerie NTL incluent la couverture globale et la haute résolution spatiale avec des pixels correspondant à moins d'un kilomètre carré. Ces résolutions élevées permettent aux chercheurs de collecter les données souhaitées aux niveaux mondial, national et régional. De plus, l'imagerie NTL offre une qualité constante partout dans le monde sans aucune manipulation politique (Bruederle, 2018).

Dans le domaine de l'estimation des stocks de matériaux à l'aide de l'AFM, Kazue et al. (2009) ont utilisé des images de lumière nocturne comme outil d'aide pour estimer le stock de cuivre utilisé dans les pays en développement d'Asie, notamment l'Inde, la Corée du Sud, la Malaisie, Singapour, Taïwan, la Thaïlande, le Vietnam et le Sri Lanka. Ils ont fait valoir que la rareté des données disponibles et la difficulté d'estimer le matériel en stock en utilisant des approches ascendantes ou descendantes de l'AFM nécessitent le développement d'une nouvelle méthode. Ils ont supposé que la présence de lumière reflète l'utilisation de matériaux



électriquement conducteurs, à savoir le cuivre. Sur cette base, ils ont corrélé les données statistiques disponibles sur les données de cuivre en cours d'utilisation avec l'accumulation de lumière sur les images satellites de Nighttime Light. Ils ont montré la faisabilité de leur méthode mais n'ont pas validé leur approche.

En utilisant des hypothèses similaires, Feng-Chi et al. (2011) ont appliqué la même technique pour le stock d'acier utilisé pour la construction d'infrastructures. Ils ont fait valoir que, contrairement au cuivre, l'acier n'est pas un excellent matériau conducteur; par conséquent, le corrélérer à la lumière nocturne ne donnera pas de bons résultats. Ils ont émis l'hypothèse que le rayonnement de la lumière nocturne serait plus fort dans les zones urbaines par rapport aux régions rurales en supposant que les zones urbaines auraient plus de zone de couverture par rapport aux zones rurales et donc plus d'éclat de la vie nocturne et, finalement, plus d'acier dans les bâtiments et les infrastructures. Ils ont mentionné que le stock d'acier dans les infrastructures des bâtiments et le rayonnement lumineux nocturne ne pouvaient être corrélés que dans les zones urbaines.

Hattori et al. (2014) ont conclu, en utilisant la lumière nocturne pour l'estimation de l'acier en service, qu'il y avait des incertitudes dans leurs résultats qui doivent être vérifiés. De même, la collecte de données sur la lumière nocturne est effectuée au moyen d'images satellites recueillies par des capteurs en fonction de leur résolution spatiale et de leur quantification qui s'améliorent avec le temps.

## **7.9. Portée mondiale et intérêts de recherche**

Il a été établi à travers une revue de la littérature disponible qu'il existe des problèmes de données spécifiques dans l'AFM. Ces questions sont différentes et présentent un problème important dans la réalisation d'études d'AFM à différentes échelles spatiales. Notamment, le manque de données à l'échelle régionale pose de nombreuses difficultés pour effectuer une analyse des matériaux et donc une prise de décision à l'échelle régionale. On savait également jusqu'à présent que les données statistiques disponibles n'étaient pas bien établies pour les

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pays en développement ou sous-développés. Il existe également un degré important d'incertitude dans les données d'entrée disponibles. Un nombre considérable d'études ont choisi de résoudre ces problèmes en utilisant d'autres outils de collecte de données. La section suivante explore plus en détail les lacunes de la recherche et les lacunes dans l'extraction des données rencontrées par les chercheurs lors de l'utilisation de méthodes secondaires dans leurs études sur l'AFM.

### **7.10. Questions de recherche et pertinence scientifique**

Il a été établi jusqu'à présent que le rôle de l'AFM est essentiel dans le bilan matières et la comptabilité des stocks. Il ressort également d'une revue approfondie de la littérature actuelle sur l'AFM que divers problèmes de collecte de données, de disponibilité et d'incertitude ont été signalés et rencontrés par les chercheurs dans leurs travaux de recherche. Ils ont essayé de résoudre ces problèmes à l'aide d'outils secondaires comme le SIG et le NTL, mais il existe encore de nombreuses lacunes dans la recherche lors de l'utilisation de l'AFM. Comme mentionné dans la section 3.2, le SIG et le NTL ont résolu quelques problèmes et amélioré la qualité des données, mais ces méthodes ne sont toujours pas en mesure de compenser le manque de données régionales. Ils sont également incapables d'obtenir des données fiables pour les parties rurales de l'infrastructure. Le problème de la collecte de données est même important dans les économies moins développées. De plus, la collecte de données sur les infrastructures de transport (réseau routier en général et chemins de fer en particulier) reste un énorme problème.

Par conséquent, il est fondamental de combiner des méthodes de collecte de données plus complètes et facilement accessibles qui peuvent améliorer l'application de l'AFM dans les pays en développement ainsi qu'à l'échelle régionale, et qui peuvent aider à l'extraction des données manquantes. À la lumière de cette discussion, nous proposons d'utiliser Google Earth comme solution pour résoudre les limitations et les incertitudes dans la collecte de données. Il est possible d'obtenir des données sur les stocks de matériel en cours d'utilisation dans les pays développés ainsi que dans les pays en développement aux niveaux de la ville, régional,

national ou mondial. Comme le montre la figure 3.1, à l'aide d'une vue 3D de la rue, il est également capable de capturer tous les types de mesures, y compris la longueur, la largeur, la hauteur et les surfaces, ce qui nous permet également de calculer les volumes. Cette vue 3D permet de visualiser la situation actuelle de la zone cible. Il peut également nous permettre d'estimer les quantités de tous les types d'infrastructures, y compris les bâtiments, les routes et les chemins de fer.

### **7.11. Objectifs de la recherche**

Il y a quatre objectifs de recherche spécifiques sous l'objectif global. Ces objectifs de recherche spécifiques étaient les suivants:

1. Revoir la littérature sur les systèmes d'infrastructures urbaines et les études d'analyse des flux de matériaux (AFM) sur les flux et les stocks de matériaux urbains;
2. Développer un modèle d'analyse de flux de matières ascendant en utilisant une méthode secondaire pour remédier aux limites des données de l'AFM;
3. Appliquer ce nouveau modèle sur le réseau ferroviaire français;
4. Estimer les stocks de matériaux métalliques et non métalliques dans les infrastructures ferroviaires françaises;

### **7.12. Développement d'une méthode d'extraction de données à partir d'une infrastructure urbaine à l'aide de Google Earth**

Dans l'organigramme (Figure 4.6), différents types de formes ont été utilisés pour représenter différentes entités. La forme rectangulaire représente le «processus», la forme losange représente la «décision», tandis que la forme parallélogramme représente les «entrées et sorties de données». Les flèches indiquent la direction de ces entités pour comprendre la séquence logique. L'organigramme est divisé en 5 phases, à savoir la description du système, la collecte de données, la validation, l'estimation et la localisation.

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**Description du système:** Cette phase indique la méthodologie générale et les sources de données qui ont été adoptées pour l'élaboration de la méthode proposée. L'infrastructure ferroviaire française est le système retenu pour les travaux de recherche. Deux types de données ont été utilisées comme données «d'entrée»; (a) Google Earth et, (b) cartes SNCF, inventaires, fiches UIC et documentation disponible. L'échantillon «processus» de sélection comprend une sélection de «n» nombre de pistes pour lesquelles les données seront collectées ultérieurement. Les critères de sélection des échantillons sont basés sur le type de piste, sa situation géographique en France et les longueurs respectives des pistes. Les critères de sélection de l'échantillon complet ont été expliqués dans les sections 4.3.

**Collecte des données:** Cette phase présente les entités structurelles pour lesquelles les données seront collectées. Ces entités incluent la longueur des pistes ainsi que leur multiplicité, le nombre de tunnels et leurs longueurs respectives, le nombre de ponts et le nombre de passages à niveau. L'échantillon sélectionné de la phase précédente est ensuite soumis à une collecte de données sur les entités ci-dessus à l'aide de Google Earth. Parallèlement, les intensités des matériaux ont également été tirées de la littérature disponible pour être utilisées pour l'estimation des matériaux dans la dernière partie des travaux de recherche.

**Vérification:** Cette phase signifie la vérification de l'approche qui a été proposée dans ce travail de recherche. En raison du temps imparti pour les travaux de recherche, de la lourdeur et des difficultés dans la collecte de données manuelles de Google Earth, l'extraction de données à l'aide de Google Earth pour l'ensemble de l'infrastructure ferroviaire française était impossible. Le système ferroviaire français, comme toute infrastructure ferroviaire, regorge de structures de génie civil tels des ponts, des tunnels et des passages à niveau sur toute la longueur des voies ferrées. Parmi toutes ces structures, les ponts et les passages à niveau sont les structures les plus fréquemment répétées qui coupent ou traversent les voies ferrées. Sur la base de leur apparition fréquente le long des trajectoires des voies ferrées, quatre paramètres

comparables ont été développés à partir des données de Google Map et de la SNCF afin de vérifier la méthode développée dans ce travail de recherche. Ces quatre paramètres sont;

- a) Kilomètre par pont pour Google Earth Data ( $K_{BG}$ ),
- b) Kilomètre par passage à niveau pour Google Earth Data ( $K_{LG}$ ),
- c) Kilomètre par pont pour les données SNCF ( $K_{BS}$ )
- d) Kilomètre par passage à niveau pour les données SNCF ( $K_{LS}$ )

La valeur de  $K_{BG}$  doit être comparée à  $K_{BS}$ , tandis que  $K_{LG}$  doit être comparée à  $K_{LS}$  à des fins de validation. L'objectif est d'obtenir une marge de différence minimale en pourcentage entre eux. En utilisant l'équation trois et l'équation quatre et le nombre de ponts et de passages à niveau dans le système ferroviaire français, donnés dans le tableau 4.2, selon l'inventaire SNCF, les paramètres  $K_{BS}$  et  $K_{LS}$  ont été calculés et sont présentés dans le tableau 4.3.

**Estimation:** cette phase traite de l'estimation du stock de matériaux dans les infrastructures ferroviaires françaises en prenant en compte plusieurs données de produit, à savoir les données de voie, de pont, de tunnel et de passage à niveau provenant de Google Earth et en les multipliant avec des intensités de matériaux provenant de diverses sources.

### **7.13. Exemples de critères de sélection de piste dans Google Earth pour l'extraction de données**

Comme expliqué précédemment, il n'est pas possible de collecter des données pour l'ensemble des infrastructures ferroviaires françaises dans ce travail de recherche en utilisant Google Earth car cela nécessite un effort et un temps importants. Des données pour une partie de l'infrastructure ferroviaire française ont été collectées. Cette portion couvre 9182,7 km (près de 32% de la longueur totale) de longueurs de pistes, ce qui comprend 95 pistes (près de 20% du nombre total de pistes).

Il est très important pour toute méthode ou modèle de recherche que les données soient représentatives du système en considération. L'infrastructure ferroviaire française est très

diversifiée et répartie dans les plaines et les régions montagneuses de France. De plus, la France compte cinq régions d'outre-mer et quelques autres collectivités et territoires (Géographie et climat, 2019). Pour avoir une représentativité des données, des critères ont été développés pour sélectionner les pistes pour lesquelles les données ont été extraites à l'aide de Google Earth.

### **7.14. Procédure de collecte de données à l'aide de Google Earth**

Cette section décrit une procédure détaillée d'extraction de données qui a été utilisée dans cette recherche à l'aide de Google Earth.

#### ***7.14.1. Repérer la piste sur Google Earth***

Dans l'interface utilisateur de Google Earth, en cliquant sur l'onglet «Obtenir l'itinéraire», vous dirigez vers un nouveau volet de boîte de dialogue qui permet à l'utilisateur d'entrer deux emplacements; A (origine) et B (destination) comme le montre la figure 4.8. Saisir l'origine et la destination de la voie sélectionnée et cliquer sur l'option de chemin de fer (figure 4.10) pour la localiser sur la carte Google en mettant en évidence son itinéraire et ses positions extrêmes à l'aide de marqueurs (figure 4.9).

#### ***7.14.2. Se déplacer sur la piste sélectionnée***

Une fois que la voie ferrée sélectionnée a été localisée sur l'interface utilisateur graphique (GUI) de Google Earth, un zoom dans le cadre vers l'origine de la voie diminue l'altitude de la vue satellite et dévoile les composants de l'infrastructure ferroviaire et le point de départ réel du piste (figure 4.11).

#### ***7.14.3. Voyager à travers la piste sélectionnée pour la collecte de données***

Une fois que l'écran et l'interface graphique sont définis sur le point de départ de l'origine de la piste sélectionnée, appuyer sur la touche avant ou arrière du clavier permet à l'utilisateur d'avancer ou de reculer avec la piste, respectivement, tandis que l'utilisation des onglets de

mouvement droit et gauche sur les claviers permet de manœuvrer la direction de la piste. En suivant la piste de la manière décrite ci-dessus, l'utilisateur peut se déplacer le long de la piste et collecter des données en observant, comptant et mesurant simplement les entités souhaitées, comme illustré à la Figure 4.12, Figure 4.13, Figure 4.14 et Figure 4.15, Figure 4.16 et Figure 4.17.

Avec l'aide de l'option 'Zoom', il est possible d'aller à n'importe quelle altitude au-dessus de la carte afin d'observer diverses caractéristiques sur ou autour de la piste sélectionnée. Il est également possible d'accéder au niveau de la rue virtuelle en utilisant l'option "Street View" juste au-dessus de l'option de zoom sur le côté droit de l'écran de Google Earth, comme le montre la figure 4.13. Sur la figure 4.14, le même pont de la figure 4.13 est illustré par l'option 'Street View' dans laquelle l'utilisateur se tient virtuellement sur le pont routier passant sur la ligne sélectionnée indiquée par une ligne bleue.

## **7.15. Estimation des stocks**

Après l'extraction des données des infrastructures ferroviaires françaises à l'aide de Google Earth, l'étape suivante consiste à estimer le stock de matériaux. La plupart des stocks présents dans ce système sont des stocks en cours d'utilisation et l'approche ascendante de l'AFM a été utilisée pour l'estimation des matériaux. Les données, dans ce travail de recherche, ont été collectées en matière de nombre de produits, c'est-à-dire ponts, passages à niveau, tunnels, etc. Dans l'approche ascendante utilisée dans ce travail de recherche pour l'estimation du stock de matériaux, le nombre de produits est ensuite multiplié par les intensités matérielles de divers matériaux dans les infrastructures ferroviaires françaises pour obtenir des matériaux estimés.

## **7.16. Description des données et résumé**

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Le tableau 5.9 présente le résumé des données collectées à l'aide de Google Earth. Sur 468 voies ferrées de l'infrastructure ferroviaire française, les données de 95 voies différentes ont été collectées. Cela représente environ un cinquième du total des voies du réseau ferroviaire français. Du point de vue numérique, il peut sembler que les voies sélectionnées représentent un pourcentage moindre du nombre total de voies de l'infrastructure ferroviaire, mais le fait est que la majorité des voies longues et importantes ont été prises en compte. Les pistes restantes sont pour la plupart des pistes de très courtes longueurs ou des pistes parallèles aux pistes sélectionnées pour des distances plus courtes ou des embranchements provenant ou convergeant vers ces pistes importantes sélectionnées. Cette explication devient plus évidente à partir de la longueur totale des pistes sélectionnées. La longueur totale des pistes sélectionnées pour les données collectées à l'aide de Google Earth s'élève à un peu moins de 9200 km. C'est plus de 31,5% de la longueur totale de l'infrastructure ferroviaire française. Pour les ressources stipulées de ce travail de recherche et le niveau de lourdeur rencontré lors de la collecte de données, ce pourcentage est un compromis correct qui permet d'analyser cette nouvelle méthode de collecte de données.

Il ressort du tableau 5.9 que les ponts ont été classés en deux catégories distinctes en fonction de leur longueur de travée; (a) ponts courts ( $<50$  m) et (b) grands ponts ( $\geq 50$  m). Bien qu'il n'y ait pas de critère général pour faire une marque de 50 mètres en tant que ligne de démarcation, mais, en général, comme observé lors de la collecte des données, la plupart des ponts ferroviaires traversant la route ont une longueur maximale de 50 m dans la plupart des cas. Par conséquent, on peut supposer, par souci de simplification lors de l'estimation des matériaux, que les ponts plus courts sont les ponts ferroviaires traversant la route tandis que les plus grands sont les ponts routiers passant sur la voie ferrée. Il convient également de noter que tous les ponts existants sur une ligne sélectionnée, qu'il s'agisse d'un pont de chemin de fer ou d'un pont routier, ont été pris en compte à des fins de simplification, laissant derrière le débat si un pont particulier fait partie de l'infrastructure ferroviaire ou du réseau routier. Au total, 7154 ponts ont été enregistrés lors de la collecte des données, dont 1990 étaient de grands ponts tandis que 5164 étaient plus courts.



Il y a 3867 passages à niveau où une voie ferrée croise une route. Il existe 145 tunnels pour la longueur des données collectées pour les lignes ferroviaires sélectionnées qui parcourent près de 115 km de voies ferrées couvertes.

### **7.17. L'analyse des données**

Cette section illustre les données selon divers paramètres. Le tableau 5.10 présente cette analyse sous une forme systématique. Tout d'abord, sur la base du principe de fonctionnement du chemin de fer, certaines voies ferrées électrifiées et non électrifiées sont comparées. En matière de nombre de pistes, 44 pistes électrifiées ont été sélectionnées tandis que 51 étaient des pistes non électrifiées mais en fonction de la longueur des pistes, un peu plus de 63% des pistes sélectionnées étaient électrifiées. Cela représente 20% de la longueur totale des voies de l'infrastructure ferroviaire française. La contribution des voies non électriques est inférieure à 37%, soit environ un dixième du réseau ferroviaire français. Les voies électriques ont 4841 ponts avec un  $K_{BG}$  de 1,20 tandis que les voies non électriques ont 2313 ponts avec  $K_{BG}$  de 1,46. De même, 1821 passages à niveau ont été enregistrés pour les lignes électrifiées par rapport à 2046 passages à niveau pour les lignes non électrifiées. La valeur respective de  $K_{LG}$  pour eux s'est avérée être respectivement de 3,19 et 1,65.

En matière d'exploitation du chemin de fer, 56 lignes mixtes tandis que 39 lignes de fret ont été sélectionnées pour la collecte de données. Les lignes mixtes représentent un pourcentage important de 92% contre un peu moins de 8% des lignes de fret. Les lignes mixtes sélectionnées représentent environ 29% de l'ensemble des infrastructures ferroviaires françaises. Les lignes mixtes ont 6755 ponts et 3343 passages à niveau avec le  $K_{BG}$  à 1,26 et  $K_{LG}$  à 2,55 respectivement. Les lignes de fret, partie moindre du réseau ferroviaire français, ont enregistré seulement 399 ponts et 524 passages à niveau. Les valeurs respectives de  $K_{BG}$  et  $K_{LG}$  pour les passages à niveau se sont établies à 1,68 et 1,28.

La valeur globale du kilomètre par pont pour Google Earth,  $K_{BG}$  se révèle être de 1,28, ce qui signifie que sur toutes les voies ferrées sélectionnées, après tous les 1,28 kilomètres, il y a un

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pont. De même, le kilomètre par passage à niveau pour Google Earth,  $K_{LG}$  a été calculé comme 2,37. Ces deux valeurs sont essentielles et seront utiles lorsque dans la section à venir ces deux valeurs seront comparées avec leurs homologues pour les données statistiques SNCF, données dans le tableau 4.3, c'est-à-dire  $K_{BS}$  et  $K_{LS}$  afin que l'approche nouvellement développée de collecte de données utilisant Google Earth puisse être vérifiée.

Le tableau 5.11 résume les données de suivi de Google Earth en fonction de la multiplicité et du type de suivi. On peut observer qu'environ 6000 km des voies ferrées sélectionnées sont des voies à double ligne dans lesquelles il y a deux rails parallèles. 2192,9 km de voies couvertes tombent sur une seule voie tandis qu'un peu plus de 1000 km de voies sont des lignes multiples sur lesquelles plus de 2 rails circulent en parallèle. Ces pistes multiples existent généralement à proximité des métropoles telles que Paris, Strasbourg, Lyon, Lille etc.

Une comparaison du pourcentage d'occurrence de ces traces est présentée dans un graphique à barres de la figure 5.1. Environ 65% des pistes sélectionnées sont en double ligne tandis que 24% appartiennent à la catégorie d'une seule ligne. Seulement 11% des pistes sont des pistes multiples. Une brève comparaison des voies sur la base du principe de fonctionnement (électricité ou pas d'électricité) et de l'exploitation (trains mixtes ou trains de marchandises) par rapport à la multiplicité des voies a également été présentée dans le tableau 5.11.

### **7.18. Vérification de la méthode**

L'un des principaux objectifs de ce travail de recherche est de développer une nouvelle approche de collecte de données à l'aide de Google Earth afin de compenser les carences rencontrées lors des études MFA. Grâce à cette nouvelle méthode, les données de près d'un tiers du réseau ferroviaire français ont été collectées avec succès à l'aide de Google Earth. Cela nous permet équitablement de tenter une vérification de la méthode, sinon une validation, basée sur les données collectées et en la comparant aux données statistiques de la SNCF.

L'idée principale derrière la vérification est basée sur la présence de deux infrastructures, à savoir les ponts et les passages à niveau dans l'ensemble du système ferroviaire français. Les ponts et les passages à niveau sont les structures les plus courantes dans l'infrastructure ferroviaire. Afin de faire la comparaison à des fins de vérification, quatre paramètres, à savoir  $K_{BS}$ ,  $K_{LS}$ ,  $K_{BG}$  et  $K_{LG}$ , ont été développés comme décrit dans la section 4.2. L'objectif est de comparer  $K_{BS}$  avec  $K_{BG}$  et  $K_{LS}$  avec  $K_{LG}$  afin de tenter une vérification de la méthode. Les valeurs de  $K_{BS}$  et  $K_{LS}$ , celles liées à la distance moyenne entre les ponts et les passages à niveau pour les données SNCF, ont déjà été données dans le tableau 4.3 qui ont été calculées à l'aide de l'équation. 3 et Eq. 4, respectivement. Paramètres associés ( $K_{BG}$  et  $K_{LG}$ ) pour les données de piste collectées à partir de Google Earth pour différents types de pistes et leurs moyennes, calculées à l'aide de l'équation. 1 et Eq. 2, ont également été présentés dans le tableau 5.10. Dans le tableau 5.12 suivant, ces paramètres ont été comparés et une brève analyse a été donnée.

Selon le tableau 5.12, la valeur de  $K_{BS}$ , c'est-à-dire le kilomètre par pont pour les données SNCF, est de 1,08. Cela signifie qu'en moyenne, tous les 1,08 km, il existe un pont dans le système ferroviaire français, calculé à l'aide de l'équation. 3. En revanche, pour les données ferroviaires collectées auprès de Google Earth dans ce travail de recherche, la valeur correspondante  $K_{BG}$  s'avère être 1,28. Ces valeurs signifient que, pour la longueur de la voie ferrée pour laquelle les données ont été collectées à l'aide de Google Earth, tous les 1,28 kilomètres en moyenne, il y a un pont. La différence en pourcentage entre ces deux valeurs est d'environ 15%.

Pour les passages à niveau, le kilomètre par passage à niveau pour les données SNCF ( $K_{LS}$ ) a été calculé à 1,67 à l'aide de l'équation. 4. La valeur correspondante pour les données collectées par Google Earth, c'est-à-dire  $K_{LG}$ , se révèle être 2,37. La différence en pourcentage entre ces deux valeurs ressort à peine inférieure à 30%. Apparemment, cette différence semble importante par rapport à celle du paramètre pont.

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Plusieurs raisons peuvent expliquer cette différence. Outre les valeurs globales de ces paramètres présentées dans le tableau 5.12, les valeurs de ces paramètres pour divers scénarios ont été résumées dans le tableau 5.13. Selon le type de pistes, les pistes qui fonctionnent à l'électricité ont un  $K_{BG}$  inférieur de 1,20 par rapport aux pistes qui ne fonctionnent pas à l'électricité qui est de 1,46. En revanche, la valeur de  $K_{LG}$  pour les pistes électrifiées est de 3,19 contre 1,65 pour les pistes non électrifiées. Conformément aux valeurs mentionnées et à l'observation des voies ferrées lors de la collecte de données sur Google Earth, il y a rarement des passages à niveau sur des voies qui fonctionnent à l'électricité. Ces voies traversent généralement les ponts ferroviaires. Par conséquent, les valeurs de Kilomètre par passage à niveau ( $K_{LG}$ ) sont plus grandes pour les voies fonctionnant à l'électricité tandis que les valeurs de  $K_{BG}$  sont plus élevées, ce qui affecte les valeurs globales de  $K_{BG}$  et  $K_{LG}$ . Des tendances similaires ont été observées pour les lignes mixtes par rapport aux lignes de fret, comme le montre le tableau 5.13.

De plus, on peut également voir que les valeurs indépendantes de  $K_{LG}$  diminuent et deviennent plus proches ou plus basses que  $K_{LS}$  si elles sont calculées en négligeant les longueurs des voies couvertes par les chemins de fer à grande vitesse (TGV) et les lignes électriques mixtes à double voie qui ont rarement un passage à niveau étant donné leur haute vitesse et priorité ceux-ci sont donnés pendant leur course. Il est évident que les valeurs de  $K_{BG}$  et  $K_{LG}$  finiront par se rapprocher de  $K_{BS}$  et  $K_{LS}$  respectivement si une plus grande longueur des données est collectée, ce qui n'était pas possible pendant le temps et les ressources limités de ce travail de recherche donné.

Par conséquent, on peut conclure que pour la partie de l'infrastructure ferroviaire française couverte par cette recherche, qui ne représente qu'un tiers de l'ensemble, ces différences se situent dans une fourchette raisonnablement acceptable pour la vérification de la méthode et cela suggère que cette nouvelle méthode de la collecte de données a beaucoup de potentiel.

### **7.19. Estimation du stock de matériaux**

Après la mise en place de la nouvelle méthode de collecte de données, l'étape suivante est son application pour l'estimation du stock de matériaux. Comme expliqué précédemment au chapitre 4, une approche ascendante de l'AFM a été employée aux fins d'estimation dans laquelle les intensités des matériaux ferroviaires ont été utilisées.

La quantité totale d'acier stockée dans la partie de l'infrastructure ferroviaire française pour laquelle les données ont été collectées via Google Earth a été résumée dans le tableau 5.15. Une grande quantité d'environ 2400 kilotonnes d'acier est stockée dans une partie couverte de l'infrastructure ferroviaire française. Cela montre que le réseau ferroviaire français est un riche dépositaire de l'acier utilisé. Pour le bois, il a été calculé que la partie couverte du réseau ferroviaire français utilise du bois entre 2274 kt et 3567 kt. Le stock de bois estimé a été résumé dans le tableau 5.17. En moyenne, une quantité substantielle de 14814 kilotonnes de granulats est présente dans la partie couverte de l'infrastructure ferroviaire française.

## **7.20. Conclusion**

### ***7.20.1. Utilité de l'analyse des flux de matières (AFM) dans l'estimation des stocks***

L'AFM est un outil très utile et polyvalent non seulement pour l'évaluation systématique des flux de matières et des stocks, mais il fournit également un terrain solide pour l'estimation des stocks de divers matériaux dans différents systèmes et infrastructures pour une gamme variée de limites de temps. Il a un grand potentiel pour aider à préparer l'inventaire des stocks de matériaux pour une anthroposphère toujours croissante. Son applicabilité et son utilité sont affectées par les lacunes dans les données résultant de nombreuses résonances telles que le manque de données au niveau régional, le manque de fiabilité des données dans les pays en développement, les incertitudes dans les données disponibles et l'indisponibilité des données d'entrée. En éliminant ces problèmes de données, l'AFM peut être rendue plus applicable dans la plupart des études.

### ***7.20.2. Comblent les lacunes dans les données AFM via des outils secondaires***

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Les problèmes de données rencontrés lors de la réalisation de l'AFM peuvent être efficacement éliminés ou réduits et des tentatives ont déjà été faites pour les résoudre en utilisant des outils et des programmes secondaires tels que le système d'information géographique (SIG) ou l'imagerie satellite Nightlight Light. Il y a beaucoup de potentiel à combiner de tels outils avec l'AFM pour éliminer les déficiences de ces données dans l'AFM.

### ***7.20.3. Emploi de Google Earth pour la collecte de données***

Google Earth est un de ces outils capables qui peut être combiné de manière rentable avec l'AFM pour la collecte des données. Il s'agit d'un programme très avancé mais convivial et simple à utiliser qui permet à l'utilisateur de collecter des données au sol avec une bonne précision. En particulier, pour les infrastructures de transport, il offre une bonne opportunité de collecter des données directes qui pourraient ne pas être disponibles dans les enregistrements statistiques. Il dispose de fonctionnalités qui permettent à son utilisateur de suivre et de collecter des informations en temps réel liées aux produits d'infrastructure, telles que les longueurs de lignes de chemin de fer ou de routes, les ponts, les tunnels et d'autres caractéristiques géologiques qui peuvent ensuite être converties en données exploitables. Ces données peuvent en outre être utilisées pour estimer les stocks de matières dans le système ou l'infrastructure concerné.

### ***7.20.4. L'infrastructure ferroviaire française, riche source de stocks de matières en service***

L'infrastructure ferroviaire française détient une grande quantité de métaux tels que l'acier et de non-métaux tels que le bois, le béton, les granulats et les matériaux en terre. Sur la base des données collectées pour un tiers du réseau ferroviaire français par la longueur des voies, on peut conclure que ce système transporte, en moyenne, 14814 kilotonnes de granulats (pierre concassée), 2274 à 3567 kilotonnes de matériaux en bois et 2402 kilotonne d'acier. Par conséquent, il est très important de suivre l'inventaire du stock de matériaux dans les infrastructures urbaines.

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## **APPENDICES**

### **A. DATA COLLECTION SHEET**

### **B. CALCULATION WORKSHEETS**

## **APPENDIX A**

This section presents a sample data collection sheet on which data collected through Google Earth has been recorded. These sheets were manually filled for each of the selected railway track. These contain all the information pertaining to the number of bridges (short and long), number of level crossings, track multiplicity and other fundamental information about each selected track e.g. Track Identification number (on SNCF map), type of the track, length of the track, origin and destination of the track.



## APPENDIX B

### I. List of Tracks with additional information

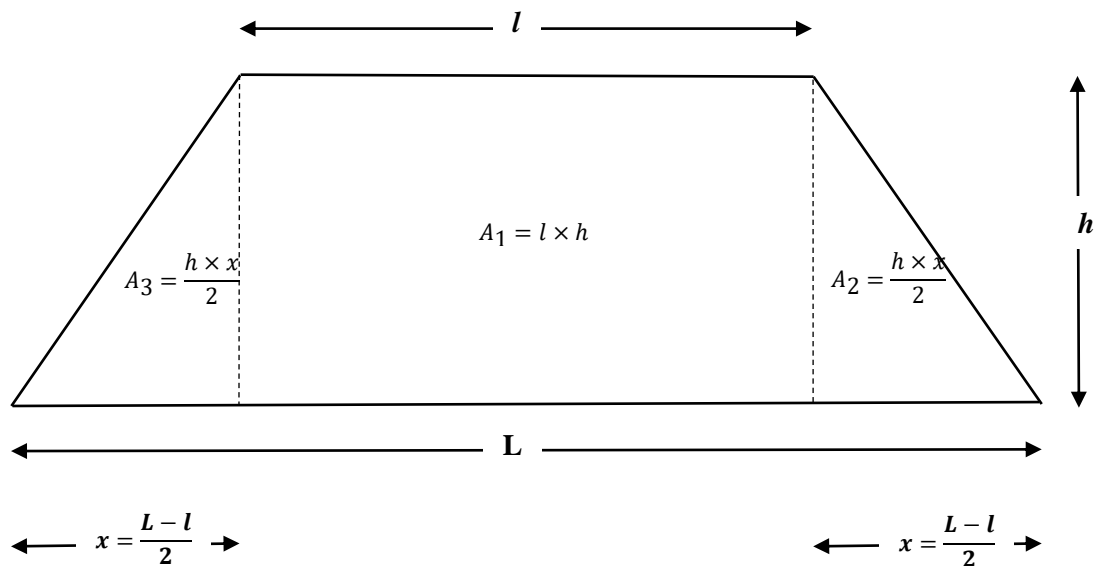
Sr. no.	Track Type	Track Identity No.	From	To	Length
-	-	-	-	-	<i>Km</i>
1	M <sub>ED</sub>	655	Bordeaux	Hendaye	231
2	M <sub>ED</sub>	450	Le Mans	Angres	97.1
3	M <sub>ES</sub>	875	Franse	Bugny	28.5
4	TGV	226	Villiers-Le-Bel	Lille	215
5	TGV	226306	-	-	10
6	TGV	216	Lille	-	136
7	M <sub>ED</sub>	269	Lille	-	14.6
8	M <sub>ED</sub> +M <sub>NS</sub>	289	Lille	Saint-Pol-Sur-Ternoise	73.5
9	MED	890	Lyon	Gaillardin	143
10	MES+MED	850	Dijon	Les Longevilles-	144
11	MED	860	Dijon	Saint-Amour	114
12	TGV	005	Strasbourg	Paris	401
13	TGV	226310	-	-	40.5
14	MED+MEM	070	Strasboutgh	Bondy	492
15	MED/MEM	272	Lille	Paris	253.5
16	MED	849	Dijon	Is-Sur-Tille	28
17	MED	142	Strasbourg	Kehl	9
18	MED	267	Lille	Hirson	123
19	MED	278	Croix-Wasquehal	Tourcoing	11
20	MED	295	Lille	Calais	108
21	MED+MEM	930	Marseille	Menton	252
22	MED	640	Bordeaux	Sete	477
23	MES+MED	650	Toulouse	Bayonne	321
24	MED	656	Puyou	Dax	31.9
25	MED	657	Arcachon	-	16
26	MED	515	Tours	Nantes	243
27	MED	468	Rennes	Redon	71.7
28	MED	321	Rouen	Amiens	114
29	MES	390	Trouville	Lisieux	29
30	MED	590	Orlean	Montauban	548
31	MED	420	Paris	Brest	647
32	MES	672	Muret	Latour-de-Carol	150.5
33	MES	669	Latour-de-Carol	Villefrance	60.5
34	MES	446	Lannion	Plouaret	17.5

## APPENDICES

Sr. no.	Track Type	Track Identity No.	From	To	Length
35	M <sub>ED</sub> /M <sub>EM</sub> /M <sub>ND</sub>	001	Paris	Mulhouse	490
36	M <sub>ND</sub>	561	Tour	Allonnes	96.3
37	M <sub>ED</sub> /M <sub>ND</sub>	530	Saintes	Nantes	254
38	M <sub>ND</sub>	783	Lyon	Le Coteau	72.4
39	M <sub>NS</sub> /M <sub>ED</sub>	905	Lyon	Marseille	285
40	M <sub>NS</sub> /M <sub>ND</sub>	110	Strasbourg	St-Die-Des-Vosges	87.2
41	M <sub>ND</sub>	145	Strasbourg	Lauterbourg	123
42	M <sub>NS</sub>	296	Marquette	Comines	14
43	M <sub>NS</sub> +M <sub>ND</sub>	648	Toulouse	Auch	83.5
44	M <sub>ND</sub>	441	Rennes	St. Malo	80.8
45	M <sub>ND</sub> +M <sub>ED</sub>	372	Tourville	Serquigny	59
46	M <sub>NS</sub>	379	Deauville	Diver-sur-Mer	20.5
47	M <sub>NS</sub>	486	Paimpol	Guingamp	38
48	M <sub>NS</sub>	725	Sévérac-le-Château	Rodez	44
49	M <sub>NS</sub>	723	Le Monastier	La Bastide	78
50	M <sub>NS</sub>	604	Poitiers	Bellac	95.5
51	M <sub>NS</sub>	606	Bellac	Limoges	43.6
52	M <sub>NS</sub>	702	Saint-Sulpice-Laurière	Montluçon	124
53	M <sub>NS</sub>	629	Libourne	Le Buisson	99.5
54	M <sub>NS</sub>	631	Agen	Périgueux	142
55	M <sub>NS</sub>	718	Toulouse	Brive-la-Gaillarde	249
56	M <sub>NS</sub>	722	Beziers	Neussargues	279.5
57	F <sub>ES</sub>	362	-	-	18
58	F <sub>ED</sub>	247	Louvroil	Feignies	6.8
59	F <sub>ED</sub>	232	Ormoy-Villiers	Longueil Saint Marie	20.3
60	F <sub>ED</sub>	935901	Rassuen	-	11.2
61	F <sub>ES</sub>	935903	-	-	6.5
62	F <sub>ED</sub>	192	Woippy	Metz	12.5
63	F <sub>ES</sub>	180611	-	-	8.5
64	F <sub>ED</sub>	159	Bening	Hargarten	26.5
65	F <sub>ED</sub>	174	Hargarten	Bouzonville	14
66	F <sub>ED</sub>	177	Bouzonville	Thionville	34
67	F <sub>NS</sub>	356	Dieppe	Envermeu	15.5
68	F <sub>NS</sub>	649	Castelsarrasin	Beaumont de Lomagne	25.5
69	F <sub>NS</sub>	785	Vichy	Puy-Guillaume	18
70	F <sub>NS</sub>	786	Vichy	Cusset	5.2
71	F <sub>ND</sub>	790	-	Gannat	24
72	F <sub>NS</sub>	782	Sainte Foy	Saint Bel	16.5
73	F <sub>NS</sub>	889	Lagnieu	Amberieu	6.3
74	F <sub>NS</sub>	904	Peyrieu	Virieu-le-Grand	21.5
75	F <sub>NS</sub>	865	Saint Bonnet	Allerey	14.3

Sr. no.	Track Type	Track Identity No.	From	To	Length
76	FNS	867	Allerey	Chalon-sur-Saone	16.2
77	FNS	868	Chaugey	Saint Aubin	8
78	FNS	294	Aire-sur-la-lys	Isbergues	4.5
79	FNS	262	Marley	Blanc Misseron	10
80	FNS	253	Saint Waast	Sous-le-bois	16
81	FNS	210	Challerange	Amagne	41.5
82	FNS	002	Esternay	Sezanne	16
83	FNS	010	Sezanne	Oiry	56.5
84	FNS	012	Troyes	Brienne	43
85	FNS	013	Brienne	Vitry-le-francois	52
86	FNS	030	Gironcourt	Neufchateau	28.5
87	FNS	928	Rognac	Aix-en-Provence	23.5
88	FNS	935902	-	-	5.5
89	FNS	935904	-	-	3.4
90	FNS	935606	-	-	6.1
91	FNS	935111	-	-	2
92	FNS	780	-	-	3.1
93	FNS	796	-	-	1.3
94	FNS	789	Saint Pourcain	La Ferte	9
95	FNS	681	La Guerche-sur-l'Aubois	Marseilles-lès-Aubigny	19

## II. Calculation of Material Intensities for Subgrade Soil



**Cross-Section of a Railway Track**



Parameter	Unit	Lower Range	Upper Range
Formation length at the top ( $l$ )	$m$	5.25	7.85
Formation length at the bottom ( $L$ )	$m$	12	20
Height of the formation ( $h$ )	$m$	0.6	1
Base of the Triangle ( $x$ )	$m$	3.375	6.075
Area of the rectangle ( $A_1$ )	$m^2$	3.15	7.85
Area of the right triangle ( $A_2$ )	$m^2$	1.0125	3.0375
Area of the left rectangle ( $A_3$ )	$m^2$	1.0125	3.0375
Cross-sectional Area ( $A=A_1+A_2+A_3$ )	$m^2$	5.175	13.925
Unit length of Track ( $d$ ) [Assumed]	$m$	1	1
Volume of unit track length ( $V = A \times d$ )	$m^3$	5.175	13.925
Density of the soil ( $\rho$ )	$kg/m^3$	1260	1500
Mass of the soil ( $m = \rho \times V$ )	$kg$	6520.5	20887.5
Mass of the soil ( $m$ )	<i>kiloton (kt)</i>	6.5205	20.8875
Material Intensity per Kilometer of Track *	$kt$	6521	20888

\* Mass of the soil ( $m$ ) has been calculated for a volume ( $V$ ) corresponding to unit length of the track ( $d$ ) i.e. 1 km of the track length. This implies that mass of the soil calculated in kilotons donates amount of material used (material intensity) for unit length (1 km in this case). In order to make it consistent with other materials considered in this research (steel, wood, concrete etc.), the material intensity has been converted to *per kilometer* by multiplying it with 1000.

# Muhammad IMRAN

## Doctorat : Systèmes SocioTechniques

### Année 2020

#### Extraction des données de stock de matériel par l'imagerie géographique dans l'AFM pour l'infrastructure urbaine

L'analyse des flux de matières (AMF) est un outil permettant d'estimer les flux et les stocks de matières et d'évaluer l'efficacité des matériaux utilisés dans les infrastructures modernes. Diverses industries ont largement appliqué l'AMF mais son utilisation est limitée en raison du manque de données régionales, de l'incertitude dans les données disponibles et du manque de données d'entrée dans certains cas. Plusieurs études ont appliqué diverses méthodes complémentaires, telles que le système d'information géographique (SIG) et l'imagerie satellite de lumière nocturne afin que la limitation des données pour l'AMF soit abordée, mais avec un succès limité, à l'exception de quelques secteurs. Dans cette étude, nous abordons ce problème en utilisant *Google Earth* comme méthode secondaire pouvant potentiellement extraire des données applicables à l'analyse des flux de matières. Cette approche de collecte des données est appliquée sur les infrastructures ferroviaires françaises en sélectionnant systématiquement 95 voies ferrées (20% du nombre total de voies) couvrant plus de 9000 km de longueur de voie (~ 31% du total) et des résultats vérifiés avec les données officielles de la SNCF sur les paramètres développés. En outre, les données extraites ont été utilisées pour estimer les stocks de matériaux métalliques (acier) et non métalliques (bois et granulats) dans la partie couverte du réseau ferroviaire français. Cette étude contribue ainsi à surmonter les problèmes de données de l'AMF et à accélérer l'application de l'AMF à plus grande échelle.

Mots clés : métabolisme urbain – stocks – chemins de fer – Google Earth – infrastructures ferroviaires – systèmes d'information géographique.

#### Material Stock Data Extraction using Geographic Imagery in Material Flow Analysis for Urban Infrastructure

Material Flow Analysis (MFA) is a powerful tool to track and estimate material flows and stocks of resources and evaluate the efficiency of the materials used in the modern infrastructure. Various industries (for example, iron and steel industry, construction industry, transportation etc.) have been applying MFA extensively. However, the use of MFA is limited largely due to the lack of regional data, uncertainty in the available data and lack of input data at all in some cases. Several studies have applied various secondary or complementary methods, such as Geographic Information System (GIS) and Nighttime Light Satellite Imagery so that data limitation for MFA is addressed but with a limited success except for few sectors (e.g., building and construction sectors). In this study, we address this issue by employing Google Earth as a secondary method that can potentially extract data applicable to material flow analysis. This data collection approach is applied on French Railway Infrastructure by systematically selecting 95 railway tracks (20% of the total number of tracks) covering more than 9000 km of track length (~31% of the total) and verified results with the official SNCF data based upon the developed parameters. Furthermore, the extracted data has been used for the estimation of metallic (steel) and non-metallic (wood and aggregate) material stocks in the covered portion of the French railway system. This study thus contributes to overcome data issues of MFA and accelerate the application of MFA on a wider scale.

Keywords: urban metabolism – inventories – geographic information systems – Google Earth – railroads – railroads, buildings and structure.

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