Master Thesis

Carbon Footprint of intra-logistics
(Distribution Centers)

Student:
Jianfei WU (0932048)

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Advisor:
Ass.-Prof. DI Dr. Norbert HAFNER

Statutory declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

0. Abstract

Along the development of human society, the problem of climate change caused by global warming was more and more significantly. Carbon emission was considered the main reason lead to global warming; therefore reducing carbon emissions (or greenhouse gases emissions) became an extremely important path to improve climate change. In order to measure and evaluate carbon emissions, the concept "carbon footprint" was proposed.

This master thesis dealing with the topic of carbon footprint of distribution centers (CF-DC) and trying to solve following two questions: How can CO_2 emissions be determined? How can it be defined work performed? To get the results of this topic, operation within distribution center system was considered as emphasis, construction of model and calculation of carbon footprint were set up as goals.

After knowing/understanding importance of reducing carbon emissions and relevant requirements, analysis of distribution center with requirements of carbon emissions was implemented. Based on the analysis, a model of distribution center system was constructed with the approach of "V-model" (Top-Down approach). This model included necessary parameters used for calculation of carbon footprint: emission mode, emission factor and activity data. Then, approach of SysML was introduced, energy consumption – another important parameter was determined, and calculation of carbon emissions was completed.

After getting the results of calculation, a brief summary was made in the end of thesis.

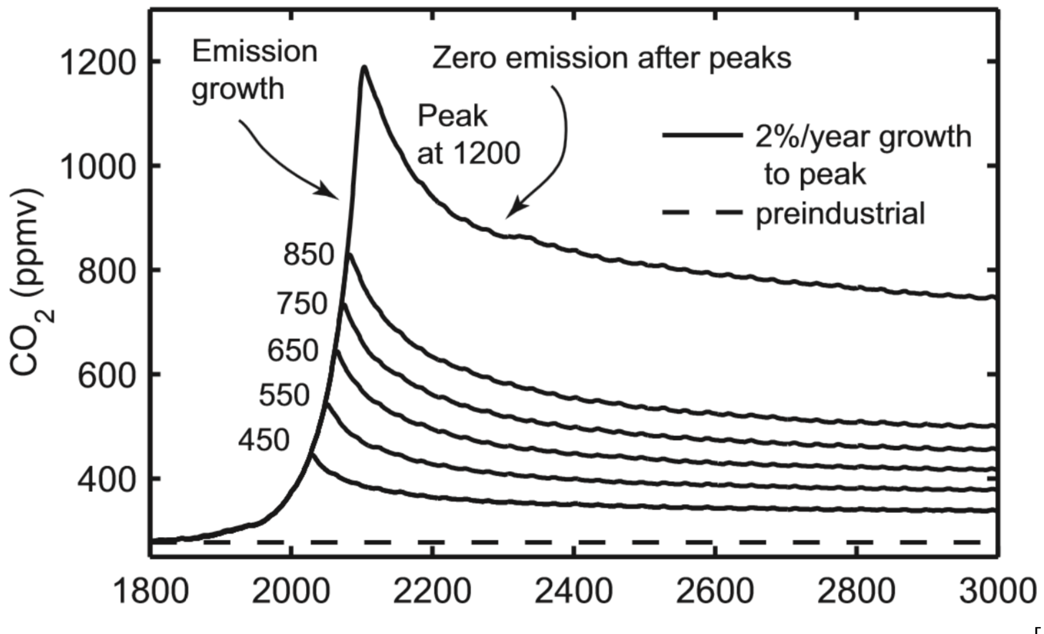
Contents

1. Introduction

CO_2 is an important greenhouse gas, warming the Earth's surface to a higher temperature and causing global climate change. CO_2 emission effects the environment significantly and becomes a long-term topic to human.

Global climate change is the most important environmental problems that human facing by far, also one of the most complex challenges that human will face in the 21st century. Especially climate warming, it is not only related to the human living environment, but also directly affect the modernization and sustainable development process of developing countries.

Recent scientific research shows that global climate warming will be aggravated in the next 100 years. It will produce more significant negative impact to the natural system and socio-economic [1] [2].How to effectively reduce carbon emissions becomes one of the focuses of attention in modern society, and produces the concept of carbon footprint that used to measure the impact of human activities to the environment.



[*Fig 1-1: Carbon dioxide changes (relative to preindustrial conditions in 1765)*][1]

Carbon footprint comes from the concept of ecological footprint, first appeared in the United Kingdom. Driven by academia, non-governmental organizations and the media, studying carbon footprint is rapidly developed [3] [4]. Normally, carbon footprint is used to calculate and illustrate carbon dioxide emissions resulted by energy consumption in all human activities.

For the human activities, commercial and logistics are extremely important parts. With the development of society and economic, distribution centers gradually becomes an important node in the commercial flow and logistics chain, its commercial and logistical status is also increasingly important. So studying the carbon footprint of a distribution center becomes an important topic. How to define a distribution center, how to determined carbon emissions, and how to analyze and calculate the carbon emissions of a distribution center are tasks of this topic.

1.1. Background

Since the 19th century industrial revolution, energy shortages, environmental pollution, ecological destruction and climate change and other environmental issues are gradually emerging, especially the climate warming problem caused by CO_2 and other greenhouse gases is most severe in the current. Global warming has caused widespread concern in the international community. The "United Nations Framework Convention on Climate Change" (UNFCCC), the "Kyoto Protocol" and the "Copenhagen Accord" demonstrate the tireless efforts of the international community in addressing global warming issues.
Among many methods of studying carbon emissions, carbon footprint is the approach that generally recognized by the international community for addressing climate change, to solve quantitative evaluation of carbon emissions intensity [4].

What is the Carbon Footprint?
The total of greenhouse gas emissions produced by an individual, an event, a product or an organization generally expressed in tons of carbon dioxide. A carbon footprint for a business could be the emissions produced in the manufacture of a product or the amount of electricity consumed for its daily operation [5].

With growth of business activities day and day, globalization becomes a general trends. Under this trend, the role of Production-oriented enterprises gradually becomes a part of global supply chain instead of global supply chain manager. This has brought great opportunities to the logistics enterprises. These logistic enterprises played a crucial role in the world commodity circulation process. As a development of logistics enterprises, distribution center not only has the function of warehouse, but also both reception and distribution functions.

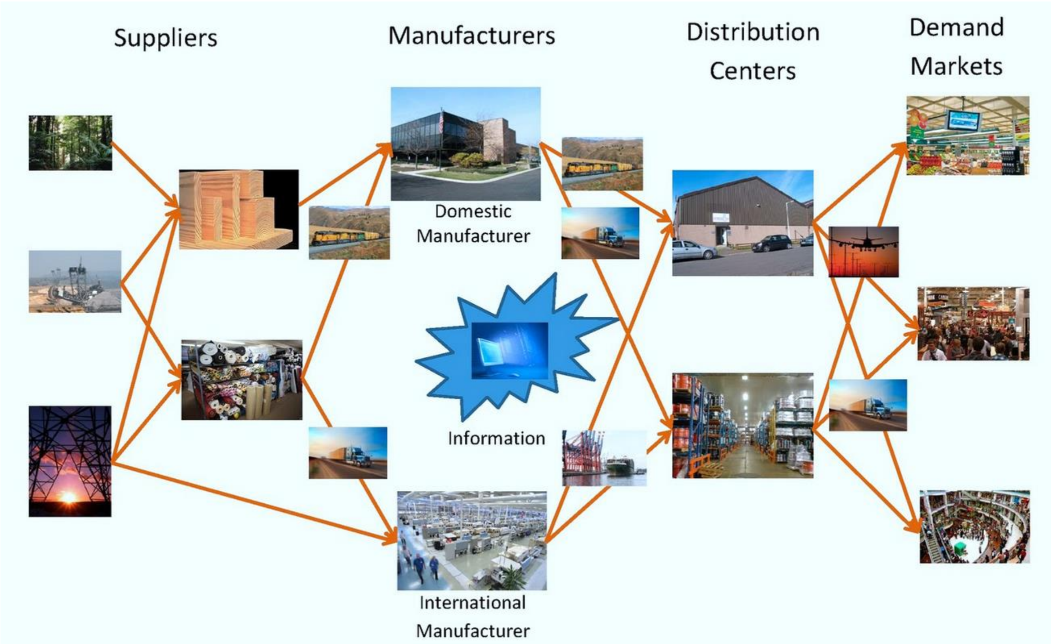
What is a distribution center?
Facility that is usually smaller than a firm's main warehouse and is used for receipt, temporary storage, and redistribution of goods according to the customer orders as they are received. It also called branch warehouse or distribution warehouse [6].

Like other enterprises or organizations, distribution center has many staffs, equipment, trucks, etc. At the same time, distribution center consumes a lot of resources, for example, energy. Truck consumes Petrol or diesel oil and then emits CO_2, human activities lead CO_2 emissions, machine running consumes energy and produces CO_2, and material discard will lead CO_2 emissions indirectly. That means a distribution center produces a lot of CO_2 or named greenhouse gases. So studying carbon footprint of a distribution center becomes a necessary task.

Studying the carbon footprint of a distribution center can calculate CO_2 emissions of a distribution center, and illustrate CO_2 emissions of every processes even every units. This result will provide support to the topic of improvement.

1.2. Delimitation

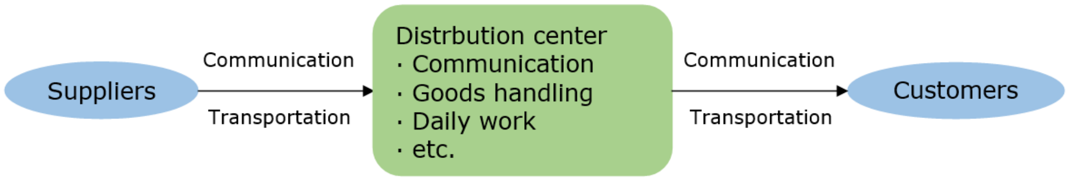
Business flows and logistic chains are complex processes. They cover the fields from materials to consumers like a huge network. As a node of business flows and logistics chain, distribution center is a complex organization (or network) too. It contains a lot of activities from its suppliers to its customers. It is a hard works to analysis all activities of a distribution center.



[Fig 1-2: Chart of sample of supply chain] [7]

Figure 1-2 shows a simple supply chain network. For a distribution center, there are many suppliers and many customers. The suppliers of a distribution center may be a factory, a warehouse, even another distribution center.

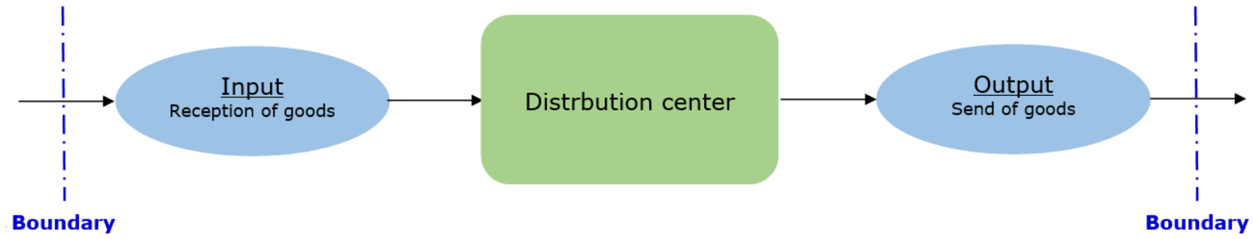
There are also different types of customers of a distribution center, individual, factory, market, or another distribution etc. As a result of simplified, a distribution center network can be considered a process as follows:



[*Fig 1-3: Processes of distribution center network*]

Here we ignore the types and quantity of suppliers and of customers. Nevertheless it looks very simply, but analysis is still a hard work, because there is much information contained in communication, transportation, suppliers and customers.

For analysis and calculation of carbon footprint, studying all activities is not an easy work, on the other hand, is also not a necessary work, because we should focus on operations of a distribution center itself. So we can make a delimitation here to ignore all activities and processes that we need not to consider. Suppliers and customers are canceled. Communication and transportation out of distribution center are also canceled. Input of distribution center is simplified to reception of goods and output of distribution center is simplified to send of goods.



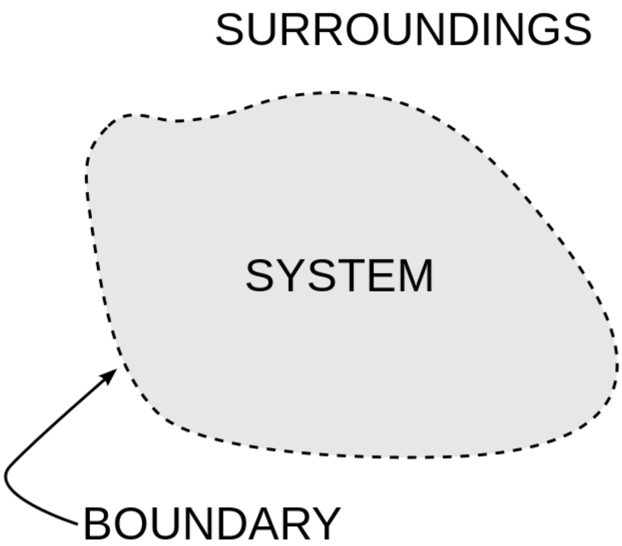
[*Fig 1-4: Boundary of distribution center network*]

Figure 1-4 shows the scope of a distribution center after delimitation. This is the distribution center system that we need to analyze and calculate.

1.3. System Definition

A distribution system is a complex organization. It contains a lot of elements like staffs, machines, materials, etc. It is difficult to describe all elements of distribution center and relationships between these elements. Normally a complex structure can be simplified to a system in order to discuss or analyze easily.

What is a system?
A system is a set of interacting or interdependent components forming an integrated whole or a set of elements (often called 'components') and relationships which are different from relationships of the set or its elements to other elements or sets [8].



[*Fig 1-5: A schematic representation of a system*] [1]

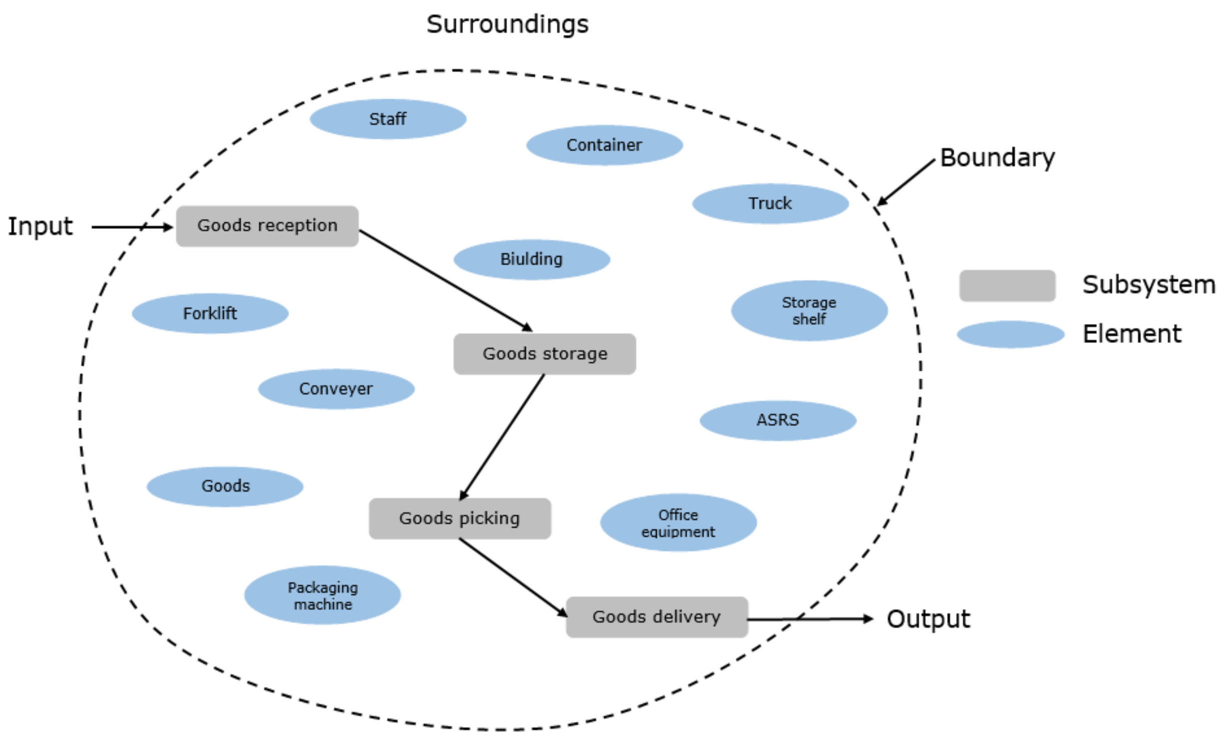
All systems have inputs, outputs and feedback mechanisms, maintain an internal steady-state (called homeostasis) despite a changing external environment, display properties that are different than the whole (called emergent properties) but are not possessed by any of the individual elements, and have boundaries that are usually defined by the system observer. Systems underlie every phenomenon and all are part of a larger system [9].

Here, we can consider a distribution center as a system. According to functions of a distribution center, some subsystems and elements are discussed as follows:

a) Subsystem
Different processes can be consider as subsystems
Goods reception process
Goods storage process
Goods picking process
Goods delivery process

Common attributes of these processes are they all contain a lot of elements, like staffs, machines, etc.

b) Elements
Staff: necessary element of a system, because staff is the operator of distribution center system.
Building: the basic infrastructure of distribution center. Dock is a part of building. Office is also a part of building.
Truck: transportation tool.
Forklift: internal transportation tool, used for goods loading and unloading, used for goods lifting.
Conveyer: the basic internal transportation tool
ASRS: Automated Storage and Retrieval System, an advanced machine used for warehouse or distribution canter.
Packaging machine: packaging tool
Office equipment: include PC, printer, etc. used for office operation and communication.
Storage shelf: storage of containers.
Goods: object handled by distribution center.
Container: storage of goods, pallet and tote.



[*Fig 1-6: Chart of distribution center system*]

1.4. Attributes of system

Before we analyze a distribution center, we need to know some information about distribution center, for example, attributes. These attributes should include attributes of components, of subsystem and of whole system.

What is an attribute?
A quality or feature regarded as a characteristic or inherent part of someone or something [10].

As definition of distribution center system mentioned before, there are 4 subsystems and 11 elements roughly in this system.

1.4.1. Attributes of distribution center

Distribution center is an organization which orders and receipts goods from its suppliers, stores goods in its warehouse, handles goods according to customers' orders, and deliveries goods to customers. It is not only a warehouse, but also has other functions like redistribution. Here some attributes of distribution center are discussed as follows:

- Location: an important strategic attribute. It affects business, but won't affect processes of the distribution center. So it is useless for our analysis.
- Size: an important attribute. It will lead quantity and specification of staffs, machines, methods of goods picking, etc.
- Type: different types will lead different infrastructure and different methods of goods picking. It relates to industry that the distribution center belongs to.
- Organization structure: will not affect processes of the distribution center.
- Processes: generally the main processes of the distribution center are the same.

1.4.2. Attributes of processes

Though different types of distribution centers have different operation processes, but in generally the main processes are the same. After delimitation, the main processes are goods reception (goods input), goods storage, goods picking and goods delivery.

- Target: results that processes should achieve.
- Resources: support from organization, include human resources, machines, information, materials, etc.
- Function: what should to do and how to do. Support to achieve target.
- Input: information, status of products, and other things get from previous process.
- Output: information, status of products, and other things transfer to the next process.

a) Goods reception (goods input)
   - Transportation
   - Unloading
   - Internal transportation
   - Unpacking
   - Check and inspection

b) Goods storage
   - Internal transportation
   - Storage
   - Maintenance
   - Inventory checking

c) Goods picking
   - Internal transportation
   - Retrieval
   - Moving
   - Picking up
   - Checking
   - Inspection
   - Packaging

d) Goods output
   - Transportation
   - loading
   - Internal transportation

1.4.3. Attributes of elements

Elements are basis of a system. In a specific system, they can't be divided into smaller units.

- Type: human, machines, materials, etc.
- Specification: qualification or parameters.
- Ability: what can do?
- Status: can or cannot be operated.
- Costs: operation costs, depreciation costs, etc.

a) Staff
   - Qualification
   - Ability
   - Relationships between staffs
   - Position

b) Building
   - Length
   - Width
   - Height
   - Structure
   - Construction materials

c) Truck
   - Size
   - Load capacity
   - Fuel consumption

d) Forklift
   - Size
   - Lift capacity
   - Fuel/electrical consumption

e) Conveyer
   - Carry capacity
   - Length
   - Width
   - Running speed
   - Structure

f) ASRS
   - Size
   - Storage capacity
   - Retrieval capacity
   - Operation speed

g) Packaging machine
   - Packaging methods
   - Packaging speed

h) Office equipment
   - Types
   - Specification
   - Functions

i) Storage shelf
   - Size
   - Storage capacity
   - Structure

j) Goods
   - Size
   - Weight
   - Packaging form

k) Container
   - Size
   - Load capacity
   - Weight

It is difficult to descript all attributes of system, subsystems and elements. Some attributes are not to influence operation of system basically. Some attributes though are important but not important for our analysis. In this topic, our target is the analysis of distribution center and the calculation of carbon footprint. We should focus on the operation of the distribution center rather than detailed steps and operation. So some of these attributes are not mentioned here, some others will not be discussed in later chapters.

1.5. Basic approach

In order to calculate carbon footprint of a distribution center, we have to analyze distribution center at first. Different types and different industries of distribution center have different statistical data, for example, number of staffs, profits, throughput, and so on. There are much information and data need to be analyzed, and this is really a huge amount of analysis. Though system definition and delimitation have already simplified the problem, but it is not enough. A large number of analyses still exist. Even we don't know which data or information we need to analyze and which needn't. So we should to select useful data and to discard useless data in order to get right (another words: typical) conclusions. Then simplifying distribution center system in further step becomes a key problem.

Question 1: How to simplify?

A model can solve this problem! As a popular method, model is usually used to analyze and solve complex problem.

What is a model?
Graphical, mathematical (symbolic), physical, or verbal representation or simplified version of a concept, phenomenon, relationship, structure, system, or an aspect of the real world. The objectives of a model include to facilitate understanding by eliminating unnecessary components, to aid in decision making by simulating 'what if' scenarios, to explain, control, and predict events on the basis of past observations [11].

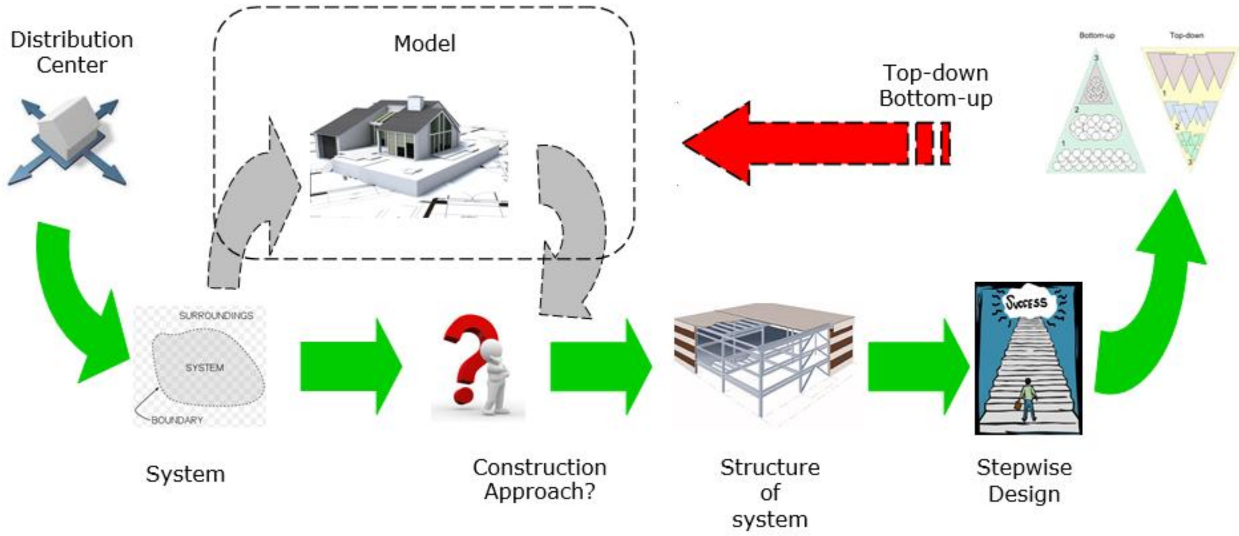
From the definition of model, we know a model can simplify a system. There are many kinds of models in the world, but there is not a uniform classification principle. In generally sense, models can be classified into physical models and nonphysical models. Another example is that these models are classified into physical models, mathematical model, structure model and simulation model according to representation forms [12].

Question2: How to construct a model?

1.5.1. Approaches of model construction

There are many approaches around the world to construct a model. For different models, there are also many approaches to provide solutions in different aspects. Such as for mathematical models, there exist analogy approach, dichotomy approach, difference approach, regression analysis approach, etc.

However, choose a suitable approach from many approaches is a troubling thing. In this topic, distribution center is considered as a system, and it has several subsystems and a dozen elements. It looks a hierarchy structure. Concerning to hierarchy structure, distribution center system is not too complex and has only three hierarchies. Basic on hierarchy structure, approaches of stepwise design or deductive reasoning could be suitable approaches. So the approaches of top-down and bottom-up are considered.



[*Fig 1-7: steps from distribution center to modelling approach*]

What is a top-down and bottom-up approach?

Top-down and bottom-up are both strategies of information processing and knowledge ordering, used in a variety of fields including software, humanistic and scientific theories (see systemic), and management and organization. In practice, they can be seen as a style of thinking and teaching.
A top-down approach is essentially the breaking down of a system to gain insight into its compositional sub-systems.
A bottom-up approach is the piecing together of systems to give rise to grander systems, thus making the original systems sub-systems of the emergent system [13].

In this topic, distribution center is considered as a system. As we analyzed above, this system has several subsystems and a dozen elements. To construct a model, we need to know the data of system, subsystems and elements. For example, number of staffs, quantity of forklifts, etc.

Here we discard the approach of bottom-up. Because if we set up all data of elements and then allocate these elements into different subsystems, the data of the system will not match with the actual distribution center system, even though the data is achieved from analysis of certain quantity of distribution centers. A big problem is which data of elements should be modified and how to modify.

In fact, for our system, we can investigate and analyze some distribution centers in order to get some overall data. These data will describe a distribution center's profile, such as size and throughput of a distribution center, and so on. Then we can analyze how many subsystems should have in the system and what these subsystems are. According to overall data, calculation of the data of elements is not a hard work. And the model constructed with these data would match the actual distribution center. Of course, this approach is top-down approach.

After the construction of model, the next step is calculation of carbon footprint of this model. This is the main task of this topic. The question arises.

Question 3: How to calculate carbon footprint?

1.5.2. Approaches of the carbon footprint calculation

What is the carbon footprint?

A measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as carbon dioxide equivalent (CO_2e) using the relevant 100-year global warming potential (GWP100) [14].

Calculation of carbon footprint can give people a clear roadmap about carbon emissions. This is helpful for reduction of carbon emissions (or greenhouse gas emissions). Many organizations and countries were paid close attention to carbon footprint and the calculation approaches. Some of them have worked out calculation approaches. But these approaches are different because consideration of aspects is different. These approaches mainly include Input-Output approach (I-O), Life cycle Assessment approach (LCA), 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPC2006), even some calculators of the carbon footprint on the web [5]. These approaches each have their own advantages, and for certain objects or in certain fields have their unique experience.

The following table shows advantages and disadvantages of different approaches.

Name of approaches	Advantages	Disadvantages
Input-Output (I-O)	● A bottom-up approach and suit for calculation of macro-level ● Calculation is simple when get data ● Integrity of the system is good	● Calculation process is rough ● Large amount of and outdated data
Life cycle Assessment (LCA)	● A top-down approach and suit for calculation of micro-level ● Calculation process is given in detailed.	● Complex of determination of life cycle stages and boundary ● Bad integrity of the system
2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPC2006)	● Detailed and comprehensive consideration of almost all emission sources of greenhouse gas ● Detailed analysis of emission principles ● Detailed calculation approaches	● Only suit for analysis of closed isolated island system ● Analysis from production aspect ● Can't calculate implicit carbon emissions in consumer aspect
Carbon Footprint Calculator on web	● Simply operation ● Easy to understand ● Close to public's life	● Not accurate enough ● Different even contradictory results between different calculators

[*Table 1-1: Comparison of different approaches*][4]

IPCC2006 is "Guidelines for National Greenhouse Gas Inventories", was edited and issued by *Intergovernmental Panel on Climate Change* (IPCC). So the IPCC2006 approach is the most suitable approach. This approach provides detailed methods of calculation of greenhouse gas. It still keeps updated and becomes internationally recognized and common assessment methods internationally.

What is the IPCC?
The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. It was established by ***the United Nations Environment Programme (UNEP)*** *and* ***the World Meteorological Organization (WMO)*** *in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts. In the same year, the UN General Assembly endorsed the action by WMO and UNEP in jointly establishing the IPCC* [15].

For distribution center system we analyzed in this topic, the emphasis is the operation of distribution center itself. As mentioned in delimitation, the boundaries of the system are reception and delivery of goods, it is not necessary to analyze and calculate carbon emissions out of the system. This system is a relative closed isolated system.

1.6. Requirements

With the development of human society and the increasing of human activities, environmental issues are increasingly prominent, especially the issue of global warming caused by greenhouse gas emissions. Based on the serious results of global warming, such as acceleration of melting of glaciers (Leading to rising sea levels), more and stronger extreme weather events (floods, droughts, heat waves, hurricanes and tornadoes), Reduction of food supply, Species extinction, human being started to focus on controlling of greenhouse gas emissions.

More and more requirements were proposed in the past decades years. More and more governments started to improve the status of greenhouse gas emissions. Though difference still exists between these governments, but some consensuses were achieved under auspices and coordination of Union Nations.

1.6.1. Global requirements – Treaties and Protocols

As the results of consensuses, there are two very important international Treaties/Protocols: UNFCCC and Kyoto Protocol. They are the basis of cooperation and coordination of countries and regions in the world on environmental issues especially on the issue of greenhouse gas emissions.

a) United Nations Framework Convention on Climate Change (UNFCCC or FCCC)[16]
   UNFCCC is an international environmental treaty, was adopted in May 1992 in New York and signed in June 1992 in Rio de Janeiro. It became effective in March 21, 1994.
   There are now 195 parties to the Convention.

b) Kyoto Protocol[16]
   The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005.
   There are now 192 Parties to the Kyoto Protocol.

There are also some other important resolutions. These resolutions were proposed as complement and development to UNFCCC and Kyoto Protocol.

a) Bali Road Map[16]
   The Bali Road Map was adopted at the 13th Conference of the Parties and the 3rd Meeting of the Parties in December 2007 in Bali. The Road Map is a set of a forward-looking decision that represents the work that needs to be done under various negotiating “tracks” that is essential to reaching a secure climate future.

b) Copenhagen Accord[16]
The COP [17], at its fifteenth session, took note of the Copenhagen Accord of 18 December 2009 by way of decision 2/CP.15.
This Accord mainly focuses on the question of carbon dioxide emissions of various countries and requests to reduce carbon dioxide emissions according to the size of each country's GDP.

c) The Doha Climate Gateway [16] - amendment of Kyoto protocol.
At the 2012 UN Climate Change Conference in Doha, Qatar (COP18/ CMP [18]8), governments consolidated the gains of the last three years of international climate change negotiations and opened a gateway to necessary greater ambition and action on all levels.

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1.6.2. Global requirements – International Standards Organization

International Standards Organization (ISO) made a series of standards to assess and measure the emission of greenhouse gases. Though these standards provided only some guidance of specification, but they can influence and require organizations, even governments of regions or countries, to improve their actions of greenhouse gas emissions.

a) ISO 14064:2006 Greenhouse gases[19]
The ISO 14064 standard is Part of the ISO 14000 series of International Standards for environmental management. It has three parts.
ISO 14064-1:2006 Greenhouse gases -- Part 1
ISO 14064-2:2006 Greenhouse gases -- Part 2
ISO 14064-3:2006 Greenhouse gases -- Part 3

b) ISO 14067:2013[19]
Greenhouse gases -- Carbon footprint of products -- Requirements and guidelines for quantification and communication

c) ISO 14404:2013[19]
It has two parts as follows:
ISO 14404-1:2013 Calculation method of carbon dioxide emissions intensity from iron and steel production -- Part 1
ISO 14404-2:2013Calculation method of carbon dioxide emission intensity from iron and steel production -- Part 2

d) ISO 13833:2013[19]
Stationary source emissions -- Determination of the ratio of biomass (biogenic) and fossil-derived carbon dioxide -- Radiocarbon sampling and determination

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1.6.3. Regions/Industry's requirements

In some regions, for example, European Union, there are some regulations and standards were issued for calculating, determining and controlling exhaust or CO_2 emissions in different industries:

a) EC 715/2007[20]
   on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information

b) EC 510/2011[20]
   setting emission performance standards for new light commercial vehicles as part of the Union's integrated approach to reduce CO_2 emissions from light-duty vehicles

c) US EPA (Environmental Protection Agency)[21]
   Series requirements for greenhouse gas emissions, for example, "Carbon Pollution Standards".

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There are a lot of requirements/regulations/laws about greenhouse gas and emissions exist in the world. Their goals are all dedicate to reduce greenhouse gas and to improve environment quality for long-term development of human.

1.7. Goals

There are two essential questions in the environment of a distribution center:

- How can CO_2 emissions be determined?
- How can the output produced by CO_2 emissions be defined?

Around above two questions, there are three tasks need to be implemented:

- Incorporation into existing CO_2 balance-assessment processes (for example, transportation systems)
- Incorporation into typical distribution centers (tasks, Logistical system/component)
- Development of concepts to measure CO_2 emissions rating of distribution centers (system boundaries, included resources, process steps for determining, calculating)

In different phases, of course, it exist different goals as phases' targets of work. They are useful for next phases. But they are not fixed and need to be modified with the progress of work. In general, there are two main goals for this topic:

Construction of Model
To construct a suitable, facility form for comprehension and for calculation, integral model of distribution center.
This is the basis of calculation of carbon footprint.

Calculation of carbon footprint
To calculate carbon footprint of the model of a distribution center with an appropriate approach, including an example by own choice for illustration. This is the final target of this topic.

2. General requirements of CO_2 emission

As we mentioned before, the greenhouse gases seriously affect Earth's climate. Humans are trying to reduce greenhouse gas emissions in order to improve the Earth's climate and the human living environment. But greenhouse gas is a widely concept, it contains a lot of gases which can affect Earth's climate.

What is a greenhouse gas?
Any of the atmospheric gases that contribute to the greenhouse effect [22]*.*

Greenhouse gases include following gases [23]:

Carbon dioxide (CO_2)
Methane (CH_4)
Nitrous oxide (N_2O)
Hydrofluorocarbons (HFCs)
Perfluorocarbons (PFCs)
Sulphur hexafluoride (SF_6)
Nitrogen trifluoride (NF_3)
Trifluoromethyl sulphur pentafluoride (SF_5CF_3)
Halogenated ethers (e.g., $C_4F_9OC_2H_5$, $CHF_2OCF_2OC_2F_4OCHF_2$, $CHF_2OCF_2OCHF_2$)
Trifluoroiodomethane (CF_3I)
Dibromoethane (CH_2Br_2)
Chloroform ($CHCl_3$)
Chloromethane (CH_3Cl)
Dichloromethane (CH_2Cl_2)
Others ……

Gas	Recent tropospheric concentration (ppm)	Increased radiative forcing (W/m^2)
Carbon dioxide (CO_2)	392.600	1.85
Methane (CH_4)	1.874/1.758	0.51
Nitrous oxide (N_2O)	0.324/0.323	0.18
Tropospheric ozone (O_3)	0.034	0.35
Others	<0.001	<0.18

[*Table 2-1: Concentrations of greenhouse gases in the atmosphere*] [24]

From the above table, we can found that CO_2 is the most important greenhouse gas. So research of CO_2 emissions is the widest studying in the world. Although carbon dioxide emissions is not the only object of studying of the greenhouse gases emissions, we called it carbon emissions or CO_2 emissions rather than greenhouse emissions customarily.

2.1. CO_2 emissions

CO_2 is the most important gas which leads to global warming. Research of CO_2 and CO_2 emissions will helpful to improve the problem of global warming.

2.1.1. Definition

What is a carbon dioxide (CO_2)?

Carbon dioxide (CO_2) is a colourless, odourless, non-combustible greenhouse-gas that contributes to global warming. It is formed by complete combustion of fossil fuels (coal, charcoal, natural gas, petroleum) and carbon containing products (such as wood), it is released also through respiration by living organisms and by the gradual oxidation of organic matter in soil [25].

Carbon Dioxide is naturally occurring chemical compound composed of two oxygen atoms covalently bonded to a single carbon atom. It is an important substance in the life and widely used in food, health, industry, and even the artificial rainfall. It can be used as food additives (food industry), as extinguishing agent, as refrigeration substance (dry ice), and so on. Because it can create lethal oxygen-deficient environments in high concentrations (especially in confined spaces), carbon dioxide has a certain degree of dangerous.

2.1.2. Mechanism

a) Generating mechanism

Mainly, carbon dioxide is produced by combustion processes, breath of humans and animals, as well as volcanic eruptions, winemaking, and so on.

Combustion of carbonaceous material will produce carbon-containing substances. Carbon dioxide is produced by complete combustion, and carbon monoxide (a kind of more dangerous gases relative to carbon dioxide) is produced by incomplete combustion.

After oxygen inhaled by animals, through cell biochemical effects, oxygen is converted to carbon dioxide and excreted. This is one kind of carbon dioxide emissions.

In Laboratory, there are many methods to obtain carbon dioxide, for example Chemical reaction of calcium carbonate (CaCO3) and hydrochloric acid (HCl).

In industry, carbon dioxide is usually obtained through Calcination of limestone with high temperature.

$$CaCO_3 \xrightarrow{\text{High temperature}} CaO + CO_2$$

Some natural events will produce carbon dioxide, e.g. Organisms (including plants and animals) in the decomposition, fermentation, decay and deterioration, volcanic eruptions, etc.

b) Mechanism of greenhouse effect
The solar radiates visible light, and these visible lights directly penetrate the atmosphere and reach the Earth's surface. Earth's surface absorbs radiation of visible lights and produces heat. At the same time, Earth's surface emits infrared rays into space in order to reduce heat until the release of heat into space and absorption of solar heat are equal.

Most gases in the atmosphere (e.g. Nitrogen, oxygen, argon, etc. named non-greenhouse gas) can't absorb visible or infrared light; therefore, these two radiations (visible or infrared light radiation) may freely pass through them, and will not be absorbed. But some gases (e.g. water vapour, carbon dioxide, etc. named greenhouse gas) in the atmosphere can absorb a part of the infrared radiation released by the earth, thus preventing radiation into space. This is well-known greenhouse effect.

Though Water vapour is the most important greenhouse gas, but with different to carbon dioxide, water vapour may condense into water. Therefore, the water vapour content in the atmosphere is basically stable, and no accumulate phenomenon like other greenhouse gases. So water vapour was not being considered when discussing greenhouse gases.

2.1.3. Hazards

Carbon dioxide is a substance with a certain hazardous. The hazards are mainly manifested in two aspects, the hazards of human body and hazards of Earth's environment.

a) Hazards of human body
Concentration levels of carbon dioxide will affect human life. If the concentration of carbon dioxide up to or over 1%, it will make people dizzy. When the concentration reaches to 4 to 5 %, people will nausea, vomiting, shortness of breath. And people will die when the concentration exceeds 10%. Carbon dioxide poisoning is rare in life, relatively, carbon monoxide poisoning is more common, and consequences are more serious.

b) Hazards of Earth's environment.
In fact, the hazards of carbon dioxide are mainly impact on the environment. As a main greenhouse gas, increase of carbon dioxide's concentrations means that the carbon dioxide will absorb more infrared

light and more heat will be left in the Earth more. This leads to changes of heat balance in the Earth and large-scale climate. These changes make people feel the deterioration of the human environment. Therefore, reducing carbon dioxide emissions and greenhouse gas concentrations in the atmosphere become common goals of human.

2.2. Carbon footprint

As mentioned before, greenhouse gas is a widely concept, it contains a lot of gases which can affect Earth's climate. Carbon footprint studies all greenhouse gases, and the result generally expressed in tons of carbon dioxide.

Generally carbon footprint focuses on total of greenhouse gas emissions produced by an individual, an event, a product or an organization. For different activities or processes, carbon footprints are different. For example, a carbon footprint for a people should be the emissions produced by breathing, a carbon footprint for a business could be the emissions produced in the manufacture of a product or the amount of electricity consumed for its daily operation.

For a process, it maybe includes many activities and/or sub-processes. When we do the calculation of carbon footprint, we should considered all activities and/or sub-processes in this process according to different generating mechanism.

Not only carbon dioxide should be calculated for calculation of carbon footprint, other greenhouse gases should be calculated too. Some major sources of greenhouse gases emissions are listed as follows [26]:

a) ENERGY
   Road transportation: NO_x, CO, and NMVOC [27]
   Public electricity and heat production: SO_2 and NO_x
   Industrial combustion: SO_2, NO_x and CO
   Residential combustion: CO
   Oil production: NMVOC, NO_x, and, CO
   Fuel combustion: NO_x

b) INDUSTRIAL PROCESSES AND PRODUCT USE
   Industrial processes can generate NO_x, CO, NMVOC and SO_2 emissions. Emissions of these gases depend on the type of process, abatement techniques, and other conditions.

c) AGRICULTURE, FORESTRY AND OTHER LAND USE
   Burning of crop residues: NO_x
   Burning of biomass: CO and SO_2
   Burning of crop residues and other plant wastes, and the anaerobic degradation of livestock feed and animal excreta: NMVOC.
   Plants, mainly trees and cereals: NMVOC

d) WASTE
   Emissions of NO_x, CO, and SO_2 are produced by
   Domestic and municipal waste incineration processes as well as the incineration of sledges from wastewater treatment: NO_x, CO, and SO_2

   NMVOC emissions can originate from
   Wastewater treatment plants and solid waste disposal on land: NMVOC

Whenever and wherever we discuss carbon footprint, all emission sources should be considered and calculated. In practices, some emissions of greenhouse gases have been converted into corresponding emissions of carbon dioxide. This will helpful to simplify the calculation of carbon footprint, and show emission levels of greenhouse gas intuitively.

2.3. Requirements

We have briefly discussed requirements about carbon dioxide/greenhouse gas emissions in previous chapter and we have roughly known some important requirements in the world.

2.3.1. Global requirements - UNFCCC

United Nations Framework Convention on Climate Change (UNFCCC or FCCC) is an international environmental treaty. The objective of the treaty is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The treaty itself set no binding limits on greenhouse gas emissions for individual countries and contains no enforcement mechanisms. In that sense, the treaty is legally considered non-binding [28].

UNFCCC is not only a treaty, but also the name of the United Nations Secretariat charged with supporting the operation of the Convention. As an organization, it committed to gain consensus through meetings and the discussion of various strategies. Following this principle, under its promotion and coordination, a series of consensus was reached in the past dozen years. Some have legally binds and well-known such as 'the Kyoto Protocol', 'the Bali Road Map' and 'the Copenhagen Accord'.

The parties to the convention have met annually from 1995 in Conferences of the Parties (COP) to assess progress in dealing with climate change. Some key steps/important achievements as follows:

a) 1994 UNFCCC [29]
   The UNFCCC is a "Rio Convention", one of three adopted at the "Rio Earth Summit" in 1992. Its sister Rio Conventions are the UN Convention on Biological Diversity and the Convention to Combat Desertification. The three are intrinsically linked. It is in this context

that the Joint Liaison Group was set up to boost cooperation among the three Conventions, with the ultimate aim of developing synergies in their activities on issues of mutual concern. It now also incorporates the Ramsar Convention on Wetlands.

b) 1997 Kyoto Protocol [29]
Full name is 'The Kyoto Protocol to the United Nations Framework Convention on Climate Change'.

In short, the Kyoto Protocol is what "operationalizes" the Convention. It commits industrialized countries to stabilize greenhouse gas emissions based on the principles of the Convention. The Convention itself only encourages countries to do so.

KP, as it is referred to in short, sets binding emission reduction targets for 37 industrialized countries and the European community in its first commitment period. Overall, these targets add up to an average five per cent emissions reduction compared to 1990 levels over the five-year period 2008 to 2012 (the first commitment period).

c) 2007 Bali Road Map[30]
The Bali Road Map includes the Bali Action Plan, which charts the course for a new negotiating process designed to tackle climate change. The Bali Action Plan is a comprehensive process to enable the full, effective and sustained implementation of the Convention through long-term cooperative action, in order to reach an agreed outcome and adopt a decision. The Bali Action Plan is divided into five main categories: shared vision, mitigation, adaptation, technology and financing.

d) 2009 Copenhagen Accord[31]
Copenhagen Accord expressed clear a political intent to constrain carbon and respond to climate change, in both the short and long term.

It contained several key elements on which there was strong convergence of the views of governments. This included the long-term goal of limiting the maximum global average temperature increase to no more than 2 degrees Celsius above pre-industrial levels, subject to a review in 2015. There was, however, no agreement on how to do this in practical terms. It also included a reference to consider limiting the temperature increase to below 1.5 degrees - a key demand made by vulnerable developing countries.

e) 2010 Cancun Agreements [32]
The Cancun Agreements are a set of significant decisions by the international community to address the long-term challenge of climate change collectively and comprehensively over time and to take concrete action now to speed up the global response.

The agreements represent key steps forward in capturing plans to reduce greenhouse gas emissions and to help developing nations protect themselves from climate impacts and build their own sustainable futures.

f) 2011 Durban Outcomes[33]
The UN Climate Change Conference in Durban was a turning point in the climate change negotiations. In Durban, governments clearly recognized the need to draw up the blueprint for a fresh universal, legal agreement to deal with climate change beyond 2020, where all will play their part to the best of their ability and all will be able to reap the benefits of success together.

g) 2012 The Doha Amendment [34] - amendment of Kyoto protocol.
Launched a new commitment period under the Kyoto Protocol, thereby ensuring that this treaty's important legal and accounting models remain in place and underlining the principle that developed countries lead mandated action to cut greenhouse gas emissions.

Under the auspices and coordination of the UNFCCC, some consensuses were gained by countries and regions in the world. These consensuses are requirements and constraints to those countries and regions about greenhouse gas emissions, and also the basis for actions of reducing emission. Only by following these requirements and constraints, the objective "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" could be realized.

2.3.2. Global requirements - Standards of ISO

What is the ISO?
ISO (International Organization for Standardization) is the world's largest developer of voluntary International Standards. International Standards give state of the art specifications for products, services and good practice, helping to make industry more efficient and effective. Developed through global consensus, they help to break down barriers to international trade [19].

The main function of ISO is to publish international standards, as well as technical reports, technical specifications, publicly available specifications, technical errata, and guides to ensure that products and services are safe, reliable, good quality. For the environment and climate change, ISO also released corresponding standards to help tackle climate change in a number of ways.

a) ISO 14000 family of standards
The ISO 14000 family of standards for environmental management is firmly established as the global benchmark for good practice in Environmental Management System (EMS), and also includes

supporting tools for environmental management and designing environmentally friendly products and services.

ISO 14001:2004 Environmental management systems – Requirements with guidance for use

Provides the requirements for environmental management systems (EMS) and contributes to an organization's objectives to operate in an environmentally sustainable manner [35].

ISO 14004:2004 Environmental management systems -- General guidelines on principles, systems and support techniques

ISO 14040:2006 Environmental management – Life cycle assessment-Principles and framework

ISO Guide 64:2008 Guide for addressing environmental issues in product standards

b) ISO series of GHG standards

The ISO series of GHG standards, which continues to expand, addresses the need for a unified framework for GHG quantification, monitoring, reporting and verification, and provides a set of auditable requirements or specifications, and in some cases recommendations, to support various stakeholder groups such as organizations, proponents of GHG emissions reduction projects, and auditors.

ISO 14064:2006

ISO 14064 is comprised of three parts. Because the standard is programme-neutral, it is not prescriptive about elements that apply to the policies of a particular GHG programme (e.g. specific additionality criteria for offset projects). These decisions are required to be made by the user of the standard (e.g. the GHG programme administrator or regulator) when applying the standard [35].

ISO 14064-1:2006 Greenhouse gases -- Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals

ISO 14064-2:2006 Greenhouse gases -- Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements

ISO 14064-3:2006 Greenhouse gases -- Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions

ISO 14065:2013 Greenhouse gases -- Requirements for greenhouse gas validation and verification bodies for use in accreditation or other forms of recognition

ISO 14066:2011 Greenhouse gases -- Competence requirements for greenhouse gas validation teams and verification teams

ISO/TS 14067:2013 Greenhouse gases -- Carbon footprint of products -- Requirements and guidelines for quantification and communication

ISO/TR 14069:2013 Greenhouse gases -- Quantification and reporting of greenhouse gas emissions for organizations -- Guidance for the application of ISO 14064-1

c) Other relative standards
Some ISO standards are intrinsically linked, such as ISO14001 and ISO9001. In this sense, for the environment and climate change, there are many related standards.

ISO 13833:2013 Stationary source emissions -- Determination of the ratio of biomass (biogenic) and fossil-derived carbon dioxide -- Radiocarbon sampling and determination

ISO 21930:2007 Sustainability in building construction -- Environmental declaration of building products

ISO 14404-1:2013 Calculation method of carbon dioxide emission intensity from iron and steel production -- Part 1: Steel plant with blast furnace

ISO 14404-2:2013 Calculation method of carbon dioxide emission intensity from iron and steel production -- Part 2: Steel plant with electric arc furnace (EAF)

……

2.3.3. Global requirements - Other international standards
Except ISO, there are a number of other international standards in the world. Although they are not as famous as ISO standards, they also have their specific significance. These standards mainly provide product-specific, validation and verification (auditing) of GHG emissions.

ISAE [36] 3000 Assurance Engagements Other than Audits or Reviews of Historical Financial Information

ISAE 3410 International Standard on Greenhouse Gas Statement

PAS [37] 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services

PAS 2060:2010 Specification for the demonstration of carbon neutrality

……

2.3.4. Regions/Nations' requirements

Different regions and/or nations have different requirements about environment and climate change. These requirements are based on some international requirements (mainly based on requirements from UNFCC). They were issued as special requirements or supplement to the international requirements.

For environmental protection and climate change, Europe paid a tremendous effort. As the EU said himself: "Since the early 1970s Europe has been firmly committed to the environment: protection of air and water quality, conservation of resources and protection of biodiversity, waste management and control of activities which have an adverse environmental impact are just some of the areas in which the EU is active, at both Member State level and internationally. Whether through corrective measures relating to specific environmental problems or cross-cutting measures integrated within other policy areas, European environment policy, based on Article 174 of the Treaty establishing the European Community, aims to ensure the sustainable development of the European model of society." [38] There are many policies/laws /programs/regulation for environmental protection and climate change, for example:

a) COM(2007) 2: "Limiting Global Climate Change to 2 degrees Celsius - The way ahead for 2020 and beyond"
b) DECISION No 406/2009/EC, on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020
c) REGULATION (EU) No 911/2010, on the European Earth monitoring programme (GMES) and its initial operations (2011 to 2013)
d) REGULATION (EC) No 715/2007, on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information

…… [38]

In other regions and nations, there are also some requirements/programs:

e) US EPA (Environmental Protection Agency) [21]
   Series requirements for greenhouse gas emissions

f) Chicago Climate Exchange (CCX)
   It was North America's only voluntary, legally binding greenhouse gas (GHG) reduction and trading system for emission sources and offset projects. [40]

   ......

All treaties, protocols, laws, regulations, standards and programs in the world committed to protect environment, reduce resource waste and improve situation of climate change. They influenced CO_2 emissions (greenhouse gas emissions) directly or indirectly. Ultimately, they are the requirements for environment protection, of course also the requirements for reduction of CO_2 emissions (greenhouse gas emissions).

After knowing or understanding these requirements, we can find that environmental protection is a difficult task and emissions reduction is an urgent work. For this topic, studying the carbon footprint of distribution center can support reduction of carbon emissions in logistical chain/business flow, and provide basic data to reach these requirements.

Though there are many requirements of greenhouse gas emissions, but for distribution centers or similar logistical warehouses, we haven't found specific requirements (standards) of greenhouse gas emissions till now. As an organization, distribution center can reference to those requirements (standards) suitable for organizations or enterprises, such as ISO14064, GHG protocol. On the other hand, related laws, regulations should be considered according to different regions that distribution centers located. Ultimately, whatever which kind of requirements (standards) be used, calculation of carbon footprint is the basic and important step.

3. Analysis of distribution center

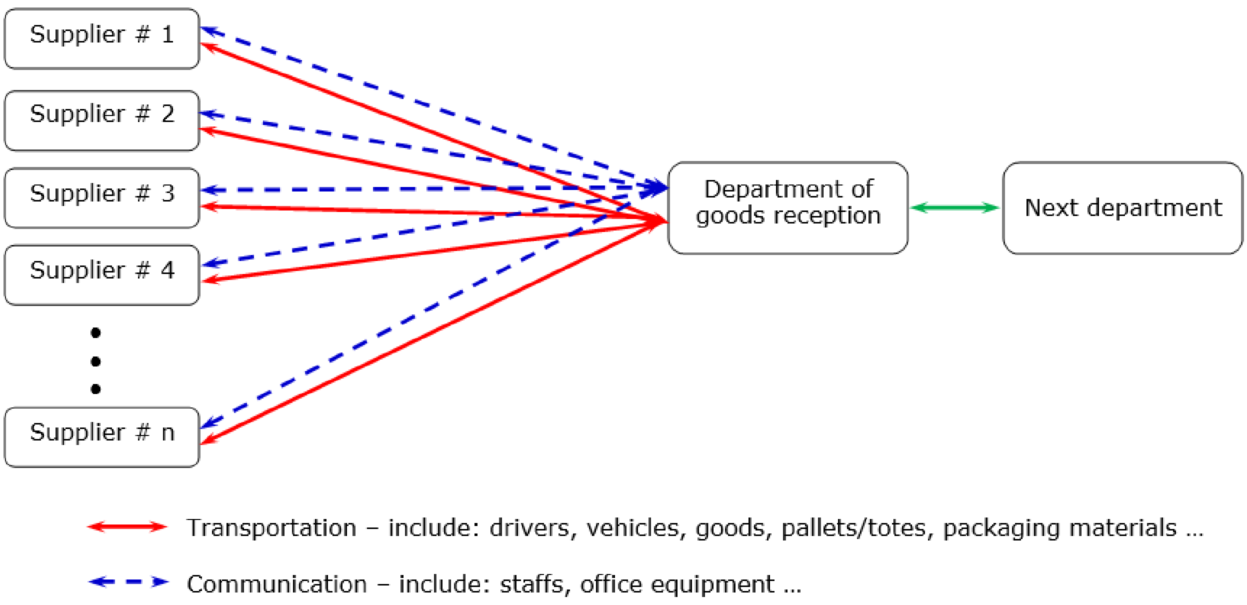
Distribution center is a complex system, it contains a lot of subsystems and components. As a rough analysis, we have discussed something (e.g. delimitation, subsystems, elements, attributes) in chapter 1. For studying carbon footprint of a distribution center, a detailed analysis for distribution center is necessary.

3.1. Boundary

From delimitation, we know the boundaries of distribution center are goods reception and good output. But for goods reception and good output, what is the boundary?

Obviously, we should focus on the operation of distribution center. So the emphases are those activities within the system, rather than those activities related to the system but outside of the system itself.

The following figure shows the whole process of goods reception.

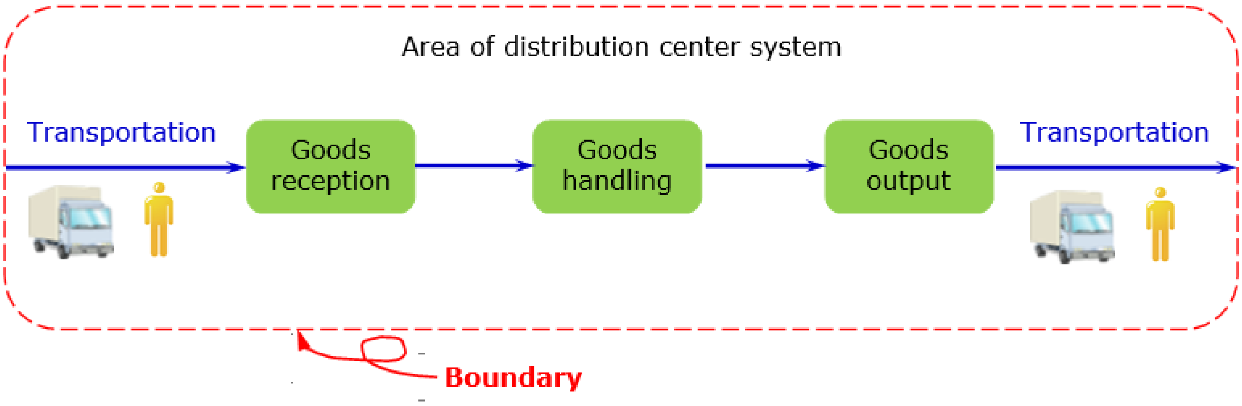


[*Fig 3-1: Processes of goods reception*]

It is not the emphasis whether drivers belongs distribution center, because we focus on the activities within the distribution center. In this sense, when drivers come into the site of distribution center, their activities must to be considered, include their vehicles moving within the area of distribution center.

Communication with supplier is daily work of staffs of department of goods reception (of course is daily work of other departments too, like purchase, inspection, and so on). In fact, the communication does not produce transfer of substances. Carbon footprint of communication mainly produces of person and office equipment. It is not effect for the definition of boundary.

Based on same consideration, the process and boundary of goods output are similar with goods reception. So the boundary of distribution center can be defined as follows: from the vehicles come into the area of distribution center till to the vehicles go away the area of distribution center.



[*Fig 3-2: Boundary of distribution center system*]

3.2. Processes

Generally, a typical distribution center has following functions: purchasing goods from suppliers, receipting goods, inspecting goods, storing goods, retrieving goods according to customers' orders, picking goods from storage units, checking/sorting goods, packing goods and sending goods to customers.

For some distribution centers with manufacturing function, they also have functions of materials purchasing and manufacturing. This type is not typical in the world, and the processes are really different for different product manufacturing. So we will not discuss this type of distribution center any more.

We can divide distribution center system into six basic processes/subsystems according to its boundary and functions:

- Goods input
- Storage
- Picking up
- Sorting
- Packaging
- Goods output

3.2.1. Goods input

After purchasing goods from suppliers, a distribution center needs to get the goods. Suppliers should to deliver goods to distribution center in time based on purchasing order. Goods reception is a basic function of distribution center.

In the process of goods input, there are some daily activities are considered:

a) Transportation of vehicles in the area of distribution center
   Though the distance of transportation is very short, but it includes fuel consumption and drivers' activities. These activities are one of the sources of carbon emissions.
   The quantity of vehicles is an important factor.

b) Goods reception
   Including following activities:
   - Unloading goods from vehicles – unloading tools should be considered (forklift and/or hydraulic manual forklift …). Different tools lead to different result, for example, basically hydraulic manual forklift will not produce carbon emissions.

   - Goods inspection – activity mainly is the operation of inspection instruments. Sometimes it includes activities of goods moving (tools should be considered).

   - Goods unpacking

   - Wastes discard – mainly are packaging materials.

c) Internal transportation
   Moving goods from one area to another area. Transportation tools are important influence factors.
   The most commonly used tools in distribution center are forklifts and conveyers.

d) Activities of staff
   Daily work, like communication, operation of equipment/instrument, and so on.

3.2.2. Storage

Before sending to customers, goods have to be stored in distribution center. So storage is another basic function of distribution center.

Mainly, there are some activities as follows:

a) Running of storage machine
   Consideration of Automated Storage and Retrieval System (ASRS).
   ASRS is popular for distribution center.

b) Internal transportation
Forklifts for Multi-shelf rack system, stacker cranes for ASRS (could be considered as one part of ASRS), and conveyers.

c) Activities of staff
Daily work, like communication, operation of equipment, and so on.

3.2.3. Picking up
After confirming customer' orders, distribution center must to find where goods that customers need are, and picking them up.

Activities consideration as follows:

a) Searching goods that customers need
ASRS has the function of retrieval, activities of searching goods are executed automatically (Running of ASRS).
For Multi-shelf rack system, manual operation is most commonly used type.

b) Internal transportation
Stacker cranes are also used in ASRS.
Moving by manual or forklift in Multi-shelf rack system.
Conveyer carries goods to picking area.

c) Picking up
Picking goods from storage unit (tote/pallet), and then put the goods into box or tote (will be sent to customer). Activities of picking up almost are manually.

d) Activities of staff
Daily work, like communication, operation of equipment, and so on.

3.2.4. Sorting
It is necessary for distribution center to confirm an order whether be executed and to confirm whether goods are correct. In this process, activities are basically manual operation.

Activities consideration as follows:

a) Internal transportation
Conveyer carries goods from picking area to sorting area.

b) Activities of staff
Daily work, like checking, confirming, operation of instrument, and so on.

3.2.5. Packaging
It is a simple process. Activities can be considered as follows:

a) Running of packaging machine

b) Internal transportation
Conveyer carries goods from sorting area to packaging area.

c) Goods packaging

d) Wastes discard
Mainly are packaging materials.

e) Activities of staff
Daily work, like packaging, operation of equipment, and so on.

3.2.6. Goods output
Sending goods to customers is final target of distribution center. This is also the most important basic function. After goods being packaged, distribution center needs to move goods into vehicles and to send them out.

Like the process of goods input, there are some basic activities should be considered:

a) Transportation of vehicles in the area of distribution center

b) Goods sending
Loading goods into vehicles – loading tools (forklift and/or hydraulic manual forklift …).

c) Internal transportation
Moving goods from packaging area to vehicles. The most commonly used tools are forklifts.

d) Activities of staff
Daily work, like communication, operation of transportation tools, and so on.

3.3. Components

A distribution center is a complex system. From the perspective of the overall, not all activities are included in above six processes. There are still some activities assisting (supporting) above six process. These activities here are analyzed as components.

- Staff
  Because human activity (mobility, commuting, etc.) is one of sources of carbon emissions, so staffs' activities must be considered. Except staffs mentioned in chapter 3.2., a distribution center need other staffs worked for management, finance, maintenance, etc.
  In this topic, we put these staffs into office staffs in order to simplify the system.
  Number of staffs is decided by size of distribution center.
  Commuting is an important activity for the daily work of staffs.

- Building
  Having an appropriate building is the basic condition of distribution center. Though building itself does not produce carbon emissions, but it influences other factors of carbon emissions. For example, the size of building influences number of lights and power of air condition.
  Building can be divided into several functional area, like storage area, office area, and so on.
  Size of building is also decided by size of distribution center.

- Office
  Office is one part of distribution center. It is a working place of staffs. In this topic, office is a wider concept. It includes all supporting function areas of distribution center, like dining room, warehouse of maintenance, lounge, and so on. This concept helps for construction of model of distribution center.
  Area of office itself does not produce carbon emissions. Except staffs, office equipment (computers, printers, telephones …) is main source of carbon emissions in office. Additionally, waste discard, paper consumption, water consumption are also sources of carbon emissions.

- Goods
  Goods are main object operated by distribution center. In general, goods itself does not produce carbon emissions. Carbon emissions of goods are mainly produced by other activities, like consumption of packaging materials, transportation, etc.
  In this topic, we focus on the operation of distribution center, rather than goods itself.

- Others
  Lights and air conditioner will be considered when discussing building.
  Waste discard, paper consumption, water consumption, consumption of packaging materials will be ignored because the carbon emissions produced by them is very small compared to other processes and activities. This assumption is helpful for analysis of carbon emissions of distribution center.

3.4. Requirements

After analysis, we need to construct a model of distribution center in order to calculate carbon emissions. This is the target of this topic.

There are some requirements to construct model.

- Defining size of distribution center.
  This is the basis of model construction. Typical distribution center should be considered and analysis. Incorrect size of distribution center will lead wrong result of model construction and wrong calculation of carbon emissions.

- Selecting an appropriate approach of model construction.
  Different approaches produce different result. An appropriate approach will helpful for simplification of model.

- Constructing model of distribution center.
  Appropriate model will helpful for calculation of carbon emissions.

For calculation of carbon emissions, there are also requirements:

- Selecting an appropriate approach.

- Defining parameters according to approach.

- Calculating.

4. Model of Distribution Center

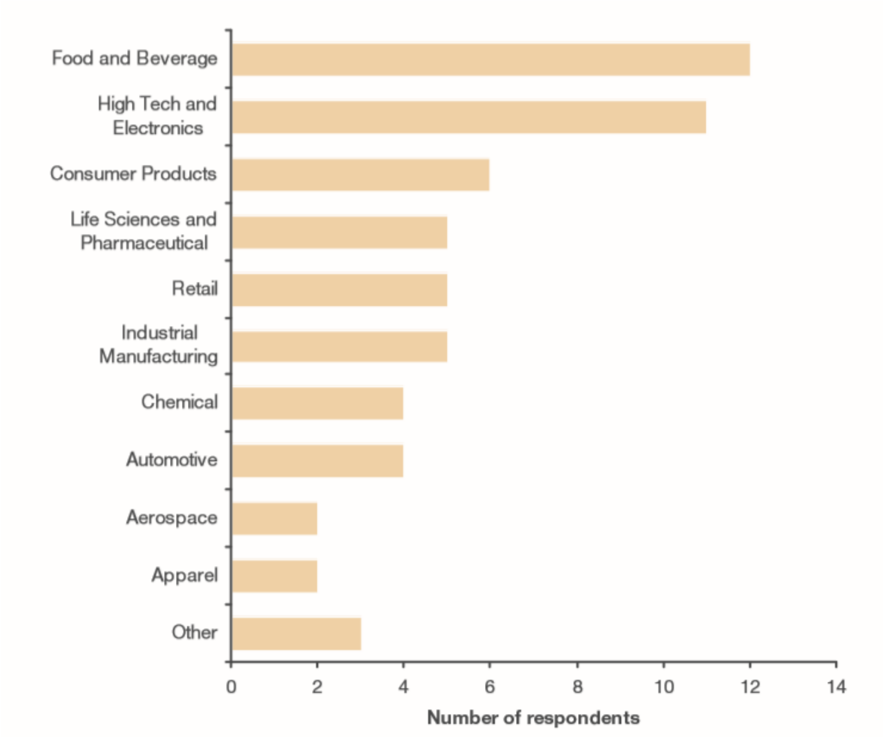
Distribution center has complex construction. It contains a lot of subsystems and elements, for example: Goods input, building, equipment …… and so on. A reality method to further calculation and analysis is to construct a model of distribution center.

In the most general sense, a model is anything used in any way to represent anything else [41]. The purposes of constructing a model are in order to simply a complex object and to facilitate the analysis and calculation. In this topic, it is very important to construct a proper model of distribution center, because it is the base of all calculations and conclusions.

4.1. Definition of Scale

4.1.1. Industry Types

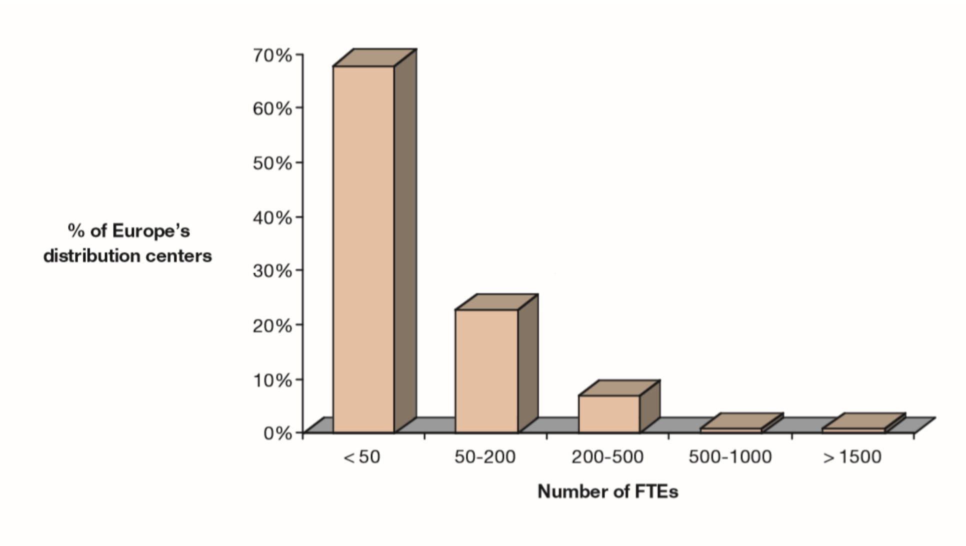
Distribution centers are usually constructed in many different industries, like Food and Beverage industry, High Tech and Electronics industry, Consumer Products industry, etc. [42] Different industry has different requirements to distribution center. For example, in Food and Beverage industry, a cold storage facility may be required.



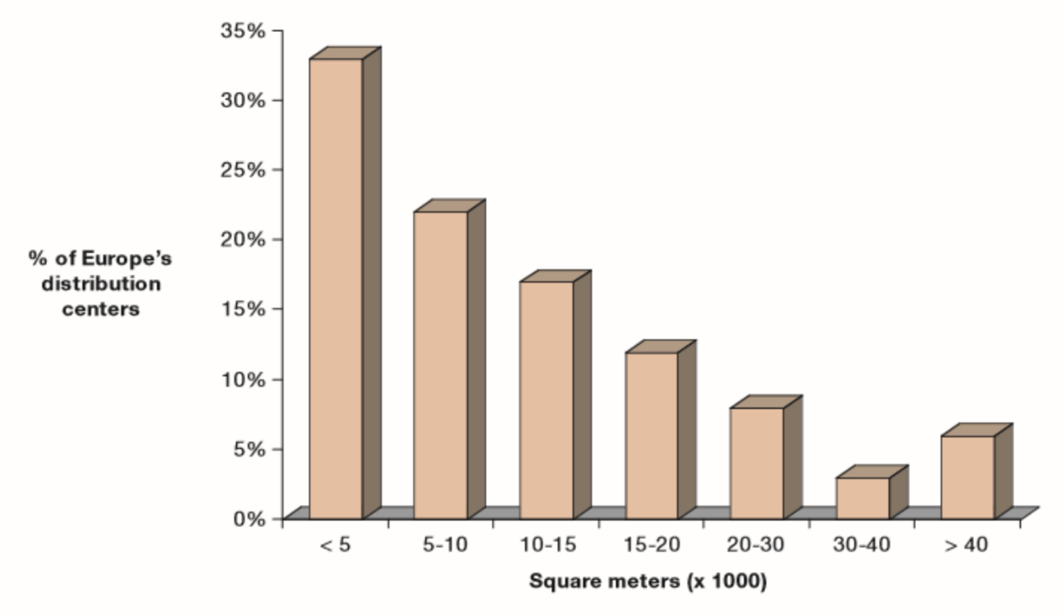
[Fig 4-1: Chart of Industry distribution] [42]

As we know, special requirements always result some special or even strange consequences and then lead to special conclusions. These consequences are obviously not the results we hope to get. So in this topic, special requirements in different industries will be ignored, instead, a general distribution center should be considered in order to get general conclusion.

4.1.2. Size of distribution center



[*Fig 4-2: Chart of employment size, FTE: Full-time Employee*] [42]



[*Fig 4-3: Chart of surface area size*] [42]

Above figures show some size data of distribution center. It is not easy to define a typical or general size of distribution center, because the size of distribution center include sales, number of employee, area, etc. In order to get a general result, some average values will be taken to descript a virtual distribution center. These data will be considered to the input of a distribution center.

Com-pany	City/ Location	Country	Number of employees of which in logistic	Throughput Inbound (Tones)	Throughput Outbound (Tones)	Area of distribution center (Net in m^2)
1	Schwabach	DE	N.A.	N.A.	3,525	8,200
2	Kassel	DE	49	3,088	3,088	N.A.
3	Kempten	DE	66	1173	1,360	N.A.
4	Bad Säckingen	DE	33	N.A.	N.A.	N.A.
5	München I	DE	6	4,398	4,408	1,397
6	Wiesloch	DE	107	5,661	5,661	21,700
7	München II	DE	23	7,904	7,327	3,637
8	Bucharest	RO	102	N.A.	N.A.	8,500
9	Dornbim	AT	N.A.	N.A.	N.A.	19,040

[*Table 4-1: Data of some Distribution center in Europe*] [43]

From above table, average values are simply calculated as follows:

Average number of employees: 55 persons
Average Throughput Inbound: 4,445 Tones
Average Throughput Outbound: 4,228 Tones
Average Area of distribution center: 10,412 m^2

The data shows that average values are not so big. Theoretically, throughput inbound and throughput outbound should be the same.

So we construct the size model of distribution center as follows:

Employees: 55 persons
Throughput Inbound: 4,500 Tones
Throughput Outbound: 4,500 Tones
Area: 10,500 m^2

It is really not a big size distribution center. In Europe, these distribution centers may be only cover few countries or regions.

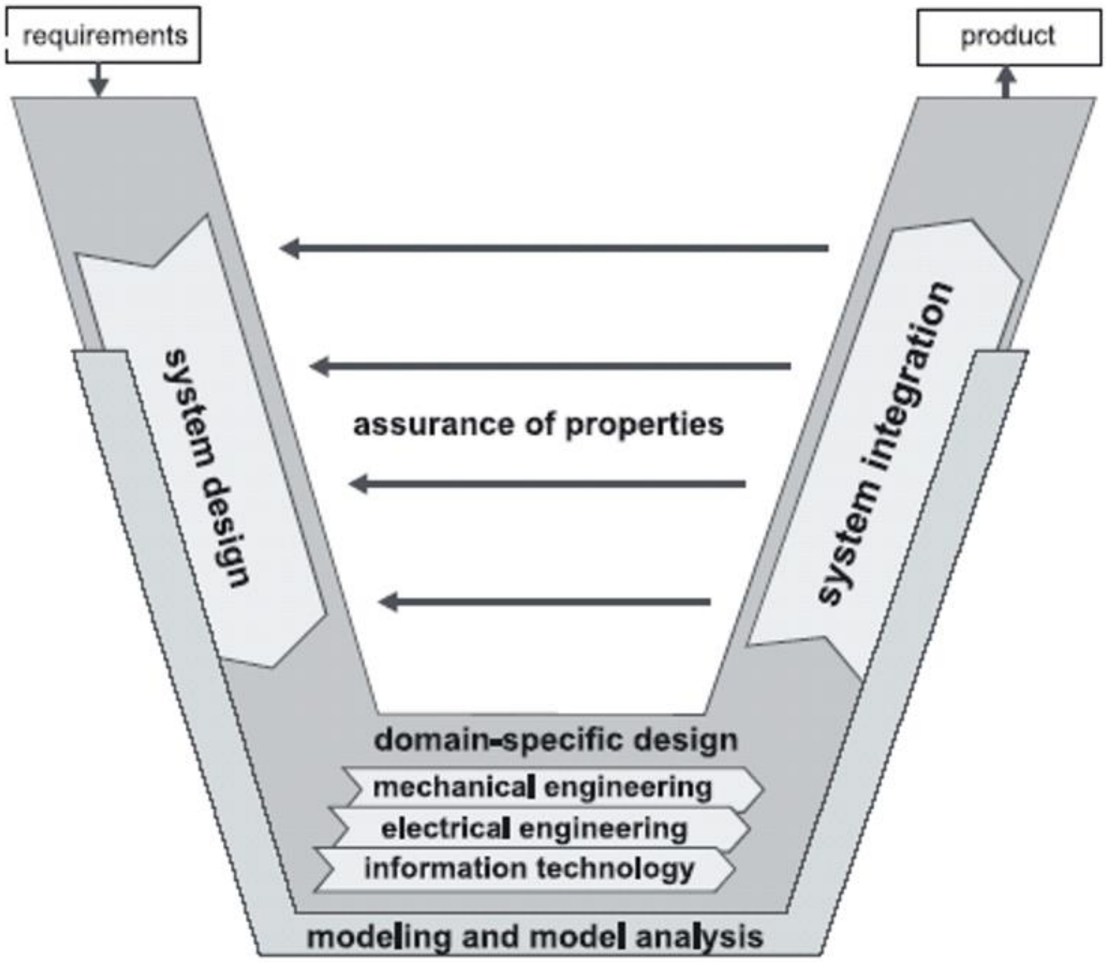
4.2. Design of a distribution center-model

4.2.1. Approach of model construction

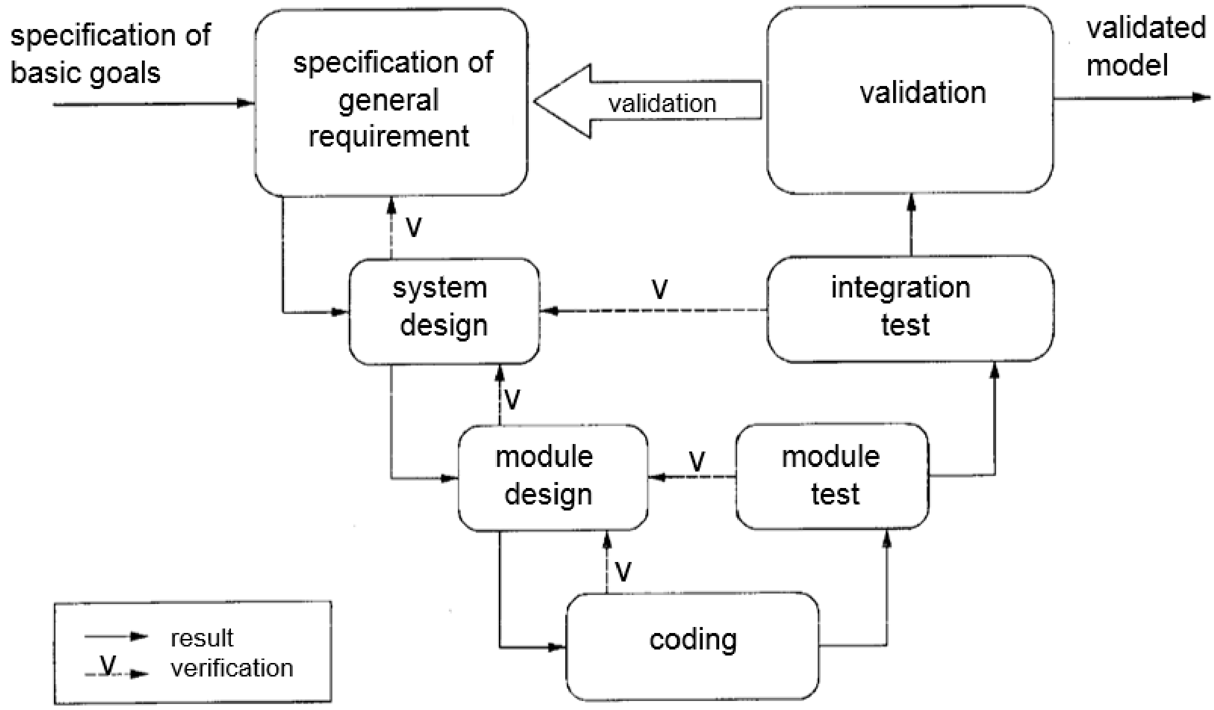
There are many approaches to construct a model in different research fields. Among these approaches, top down approach is a popular approach used in a variety of fields including software, humanistic and scientific theories, and management and organization. V-model is one of top down approach.

What is a V-model?
The V-Model is a term applied to a range of models, from a conceptual model designed to produce a simplified understanding of the complexity associated with systems development to detailed, rigorous development lifecycle models and project management models [44].

Here, as a top down approach, V-model is applied.



[*Fig 4-3: Top down approach: V-model as a macro-cycle*] [45]



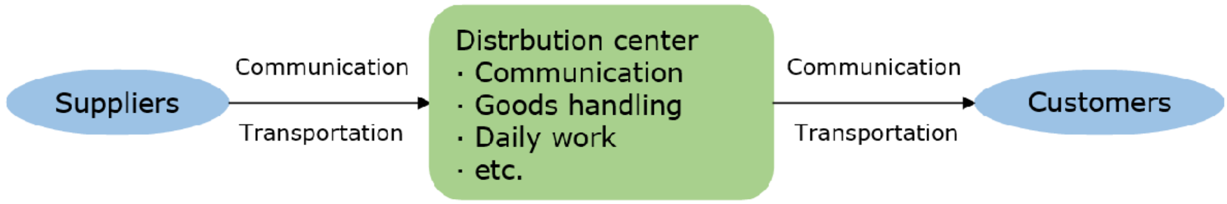
[*Fig 4-4: Top down approach: V-model*] [46]

4.2.2. Model construction

When constructing a model, we should consider a data-calculation-model. It means that the model is not only a simplified digital model but also a model includes data and parameters about calculation of carbon footprint.

4.2.2.1. General requirements

As an important node in supply chain, a typical distribution center is not only a warehouse, but also a link or centers that connecting suppliers and customers. On the other hand, how to calculate carbon footprint of distribution center is required.



[*Fig 4-5: General process of distribution center*]

As we know, Anthropogenic CO_2 emissions (i.e., emissions produced by human activities) come from combustion of carbon based fuels, principally wood, coal, oil, and natural gas [47]. Based on definition of distribution center system, CO_2 emissions are mainly produced by fuel consumption, power consumption and human breathing in this system. Here, we ignore discards and wastes caused by distribution center due to very low discards and wastes.

Based on the situation in business flow and supply chain, a distribution center is required to have following requirements (functions):

a) Transportation
   Goods transportation among suppliers, distribution and customers
   Internal transportation
   Modes and parameters of CO_2 emissions
b) Communication
   Information communication with suppliers and customers
   Internal communication
   Modes and parameters of CO_2 emissions
c) Goods handling
   Getting goods from suppliers
   Storing goods
   Picking up goods according to customers' order
   Sorting and checking goods
   Packaging goods
   Sending goods to customers
   Modes and parameters of CO_2 emissions

Additionally, some requirements on the whole should be considered:

a) Buildings
   Providing an infrastructure to distribution center
   Including office
   Modes and parameters of CO_2 emissions
b) Office equipment
   Providing basis conditions for distribution center
   Modes and parameters of CO_2 emissions
c) Energy consumption
   Air conditions
   Lights
   Commuting
   Modes and parameters of CO_2 emissions

4.2.2.2. Design of distribution center system

According to the general requirements of distribution center mentioned above, we should consider to construct some subsystems/processes to meet these requirements. These subsystems/processes can be considered as modules and must cover all functions and relative data of CO_2 emissions of a typical distribution center, and should be as simple as possible in order to analyze and construct a model.

Subsystems/Processes (modules) are considered as follows:

a) Goods input

- Functions:
  - Connection between suppliers and distribution center
  - Transportation
  - Goods receiving
  - Internal transportation
- Range:
  Starting from transportation to storage area
- Facilities and equipment:
  - Trucks
  - Docks
  - Forklifts
  - Conveyers
- Mode of CO_2 emissions
  - Trucks – fuel consumption
  - Docks – no CO_2 produced
  - Forklifts – Power consumption
  - Conveyers - power consumption

b) Storage

- Functions:
  - Connection between goods input area and picking up area
  - Internal transportation
  - Storage
- Range:
  Starting from goods input area to picking up area
- Facilities and equipment:
  - Storage system
  - Forklifts
  - Conveyers
- Mode of CO_2 emissions
  - Storage system – power consumption
  - Forklifts – power consumption
  - Conveyers - power consumption

c) Picking up:

- Functions:
  - Connection between storage area and sorting area
  - Internal transportation
  - Picking up goods according to customers' order
- Range:
  Starting from storage area to sorting area
- Facilities and equipment:
  - Automated picking system
  - Conveyers

- Mode of CO_2 emissions
  - Automated picking system – power consumption
  - Conveyers - power consumption

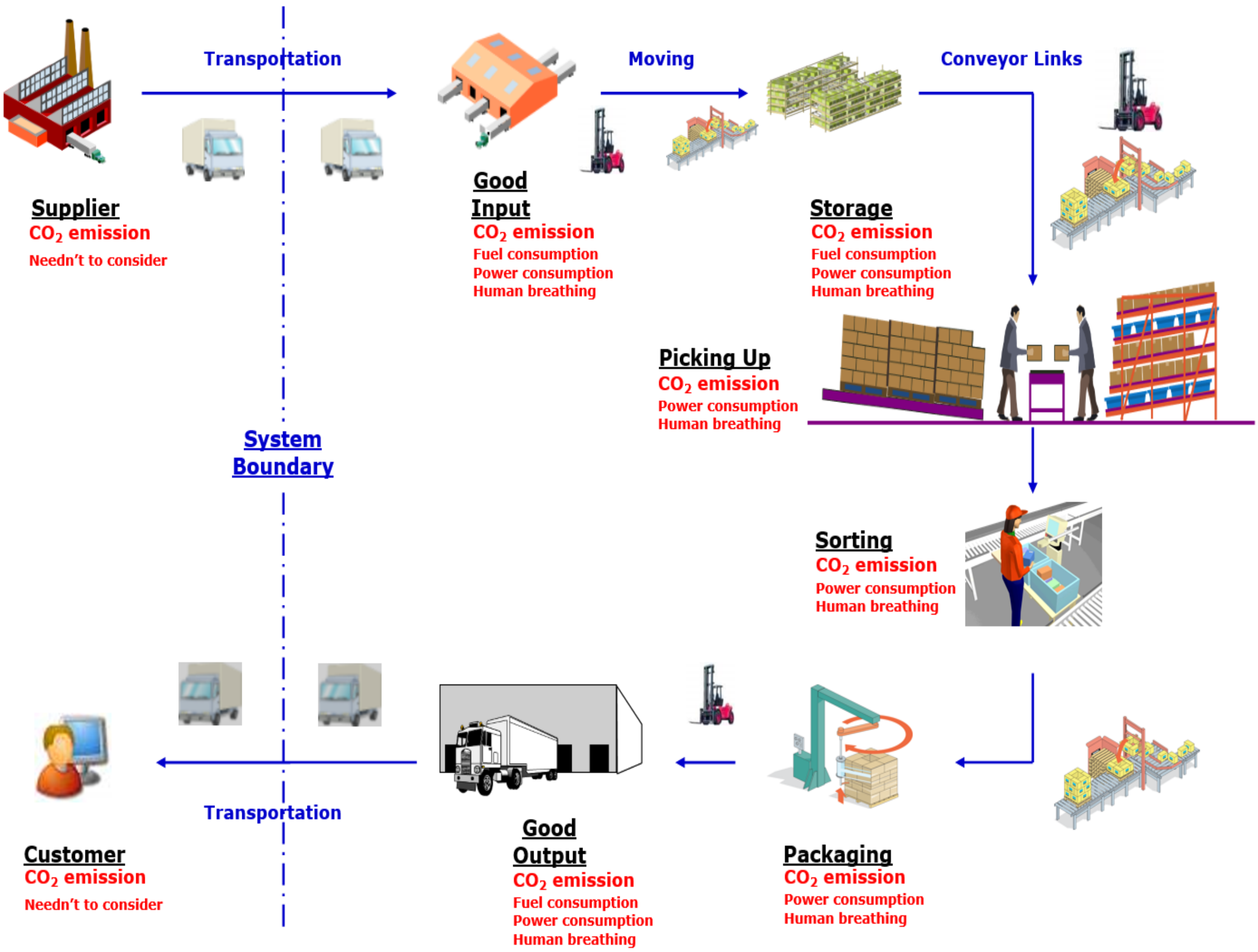
d) Sorting:
- Functions:
  - Connection between picking up area and packaging area
  - Internal transportation
  - Goods sorting and checking
- Range:
  Starting from picking up area to packaging area
- Facilities and equipment:
  - Sorting system
  - Conveyers
- Mode of CO_2 emissions
  - Sorting system – power consumption
  - Conveyers - power consumption

e) Packaging: starting from sorting areas to goods output area
- Functions:
  - Connection between sorting area and goods output area
  - Internal transportation
  - Goods packaging
- Range:
  Starting from sorting area to goods output area
- Facilities and equipment:
  - Packaging machine
  - Conveyers
- Mode of CO_2 emissions
  - Packaging machine – power consumption
  - Conveyers - power consumption

f) Goods output: starting from packaging areas to transportation
- Functions:
  - Connection between customers and distribution center
  - Transportation
  - Goods sending
  - Internal transportation
- Range:
  Starting from packaging area to transportation area
- Facilities and equipment:
  - Trucks
  - Docks
  - Forklifts
- Mode of CO_2 emissions
  - Trucks – fuel consumption
  - Docks – no CO_2 produced
  - Forklifts – power consumption

g) Other considerations:
- Staffs (mobility, Commuting)
- Office
- Office equipment
- Energy
- System boundary
- Mode of CO_2 emissions
  - Power consumption
  - Fuel consumption
  - Human mobility

h) Processes of distribution center and possible modes of CO_2 emissions



[*Fig 4-6: Processes of distribution center system and possible modes of CO_2 emissions*]

4.2.2.3. Precondition and assumption

To construct a model, we should to standardize some parameters of elements or modules in the system. Because it will lead to failure if we consider a large number of various parameters of these elements/modules, we could unify/integrate the data/parameters of similar elements/modules. Setting up some preconditions and estimations is necessary and helpful to model construction.

a) Calculation factors of carbon footprint
Generally, carbon footprint can be calculated with the basic equation (reference to IPCC2006) as follows:

$$\text{Emissions} = AD \bullet EF \bullet EC$$

- AD: Activity Data, information on the extent to which a human activity takes place
- EF: Emission Factors, coefficients which quantify the emissions or removals per unit activity
- EC: Energy consumption

So the consideration of model construction must include activity data and emission factors. And then we can define energy consumption and do the calculation of carbon footprint.

b) Transportation tools
- All transportation actions which from suppliers to distribution center and from distribution center to customers use trucks.
- All trucks are van trucks (24-feet Straight Trucks), specification as follows [48]:
  - Length: 24 feet (7.32 meters)
  - Width: 98 inches (2.49 meters)
  - Height: 102 inches (2.59 meters)
  - Tare weight: 10,000 pounds (4.54 tones)
  - GVW: 26,000 pounds (11.79 tones)
  - Capacity: 1,550 cubic feet (43.89 cubic meters)
  - Fuel type: Diesel [49]
  - Fuel consumption: 23.52 Liters/100 km (10 MPG) [49]
- Average payload per truck is 5 tones

c) Internal transportation tools
There are two types for internal transportation, forklift and conveyer.
- Forklift
  Consideration of indoor working, air pollution and safety, all forklifts in this system/model are Electric forklift, specification as follows (Example: Linde E20) [50]:
  - Load capacity: 2.0 tones

- Lift height: 3.15 meters
- Power consumption: 6.4 kWh/h

- Conveyer
  Assumption is power roller conveyer, specification as follows (Example: Cisco-Eagle 199-CRR, 1 unit) [51]
  - Width: 616 mm (24-1/4”)
  - Length: 7.62 or 15.24 meters (25’ or 50’)
  - Load capacity: 567 kg (1250 pounds)
  - Power consumption: 0.373 kW (Motor-1/2 HP per unit)

d) Pallet
The pallet is standard European pallet
- Dimension: 1,200*800*144 mm [52]
- Load capability: average 600 kilograms

e) Tote
The standard tote in Europe:
- For transportation or storage
- Dimension (Length*width): 600*400 mm [53][54]
- Height: 300mm [54]
- Load capability: 25/50 kilograms [54].

f) Automated Storage and Retrieval System (ASRS)
An Automated Storage and Retrieval System (ASRS) is an advanced and integrated system for storing and handling goods. It integrates the functions of storing, moving, searching and picking goods. It uses computer to control and manage goods, and is a high-automation system. It has many advantages like high-density storage space, high picking speed, labor costs reduction, etc. It is suitable for a warehouse, especially for a distribution center.
Assumption and relative calculation as follows:
- Area: 4250 m^2 (85*50 meters)
- Height: 10 meters
- Lays: 25 layers of shelf (0.4 meters high per layer)
- Racks: 18 units (1.5 meters wide: 2 racks/unit)
- Aisle: 17 units (1.3 meters wide)
- Stacker crane: 17 units
- Storage capacity: 4,068 storage units per layer (4,068 totes)
- Total 101,700 storage units (101,700 totes)

Assumption and calculation of power consumption are difficult because ASRS includes a lot of motors, sensors and control circuits. After analysis, we can found main power consuming devices are concentrated in stacker cranes. So the power consumption of the whole system could be estimated by power consumption of all stacker cranes and of a set of control circuits. Here the example of stacker crane is single-mast stacker crane.

- Power consumption – calculation and assumption

Name	Devices	Power (kW)	Quantity	Total (kW)	Note
Stacker crane*	Lift motor[55]	0.97	1	0.97	Squirrel-cage rotor
	Horizontal motor	0.97	1	0.97	
	Bridge motor[55]	0.25	1	0.25	
	Trolley Motor[55]	0.25	2	0.5	
	Rotate Motor[55]	0.09	1	0.09	
	Sensor	0.067 [56]	39[57]	2.62	
	Control circuit	1	1	1	Assumption
Whole control circuit	Control circuit	10	1	10	Assumption

* Motors and sensors work in a short time, actual working time should be considered when calculating total power consumption

[*Table 4-2: Assumption and calculation of power consumption of ASRS*]

g) Packaging machine
Assumption is semi-automatic packaging machine.
- (Semi-Automatic Film Wrapping Packaging Machine XT4502) [58]
- Turntable motor: 750 Watts
- Film-rack lift motor: 180 Watts
- Max. packaging weight: 2000kg
- Diameter of turntable: 1500mm

h) Air condition
Assumption is central air condition unit.
- Power consumption per unit area: 32 Watts per m^2 [59]
- Total power consumption: 336 kW

i) Personal Computer
Assumption is Apple MacBook: 58-60 Watts [60]

j) Printer
Assumption is inkjet printer: 110 Watts [61]

k) Dimensions of all goods are suit for standard tote or for multi-shelf rack, and all goods can be picked up by automated picking machine.

l) Passenger cars used for commuting consume gasoline.
- Fuel type: Gasoline [62]
- Fuel consumption: 5.8 Liters/100 km (average of EU-27) [62]

4.2.2.4. Design of distribution center module

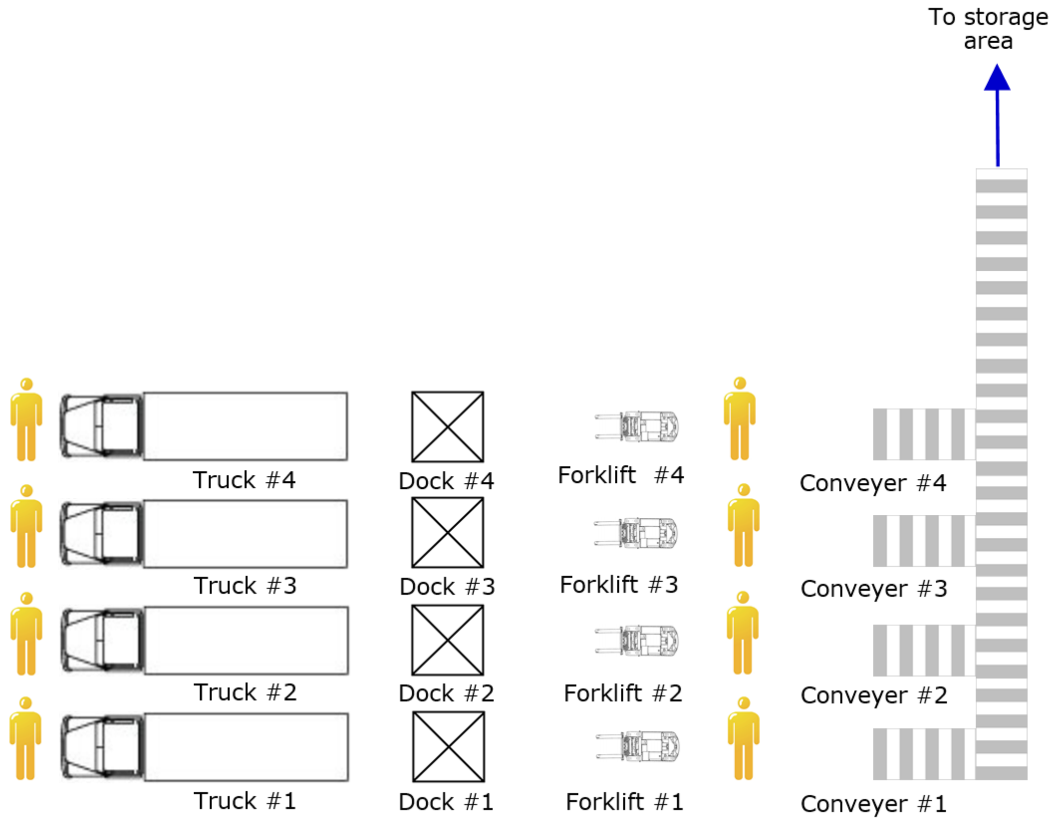
According to analysis above, some data of a distribution center system can be calculated or estimated. These data will support to construct a model of distribution center.

a) Goods Input
- Calculation and assumption
  According to the above throughput quantity, some values of inbound are calculated as follows:
    - 86.5 tones per week (52 weeks per year)
    - 17 trucks per week
    - 3.5 trucks per day (5 days per week)
- Consideration:
    - Peak condition, for example, double than usual (according to season)
    - Truck waiting time (according to unloading speed)
    - Working time
    - Internal transportation
    - Different suppliers
    - Distance of internal transportation of truck, forklift and conveyer
    - Relative operation
- Data and parameters of CO_2 emissions

Name	Q'ty	Mode of CO_2 Emissions	Emission Factors	Activity Data	Note
Dock	4	-	-	-	- Maximum Status: 4 trucks unloading goods at the same time - No CO_2 produced
Truck	4	Fuel consumption	Emissions weight/ Fuel consumption	Fuel consumption per 100 km (MPG)	- 1 truck corresponds to 1 dock - Consideration: • Distance within system boundary
Forklift	4	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- 1 forklift corresponds to 1 dock - Consideration: • working time
Conveyer	8*	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- 1 conveyer corresponds to 1 dock - Consideration: • Length/Distance • working time • Power consumption per hour
Staff	8	Human mobility	Emissions weight/ Human activities	Average emissions per hour	- 4 truck drivers and 4 forklift drivers - Consideration: • Working time • Workload

[*Table 4-3: Data and Parameters in Goods Input process*]

* Consideration:
7.62 meters length per unit (conveyer), assumption is 8 units within Goods Input.



[*Fig 4-7: Model of Goods Input*]

b) Storage

The capability of pallet is 600kg (assumed preconditions), that means in inbound docks and outbound docks each have 144 pallets to be handled per week or 29 pallets to be handled per day. In another calculation are 4,325 totes per week or 865 totes per day.

There are two storage methods in distribution center. One is traditional storage method. Some goods cannot be divided into small units or light units to suit for ASRS, and these goods need to be stored or transported with special way. In this model, we consider a multi-shelf rack system and forklifts to resolve this problem. Another method is to utilize the function of ASRS because storing goods is an important function of ASRS.

- Calculation and assumption

Calculation of storage requirement of a distribution center is a complex process. Here is only a simple assumption based on area:

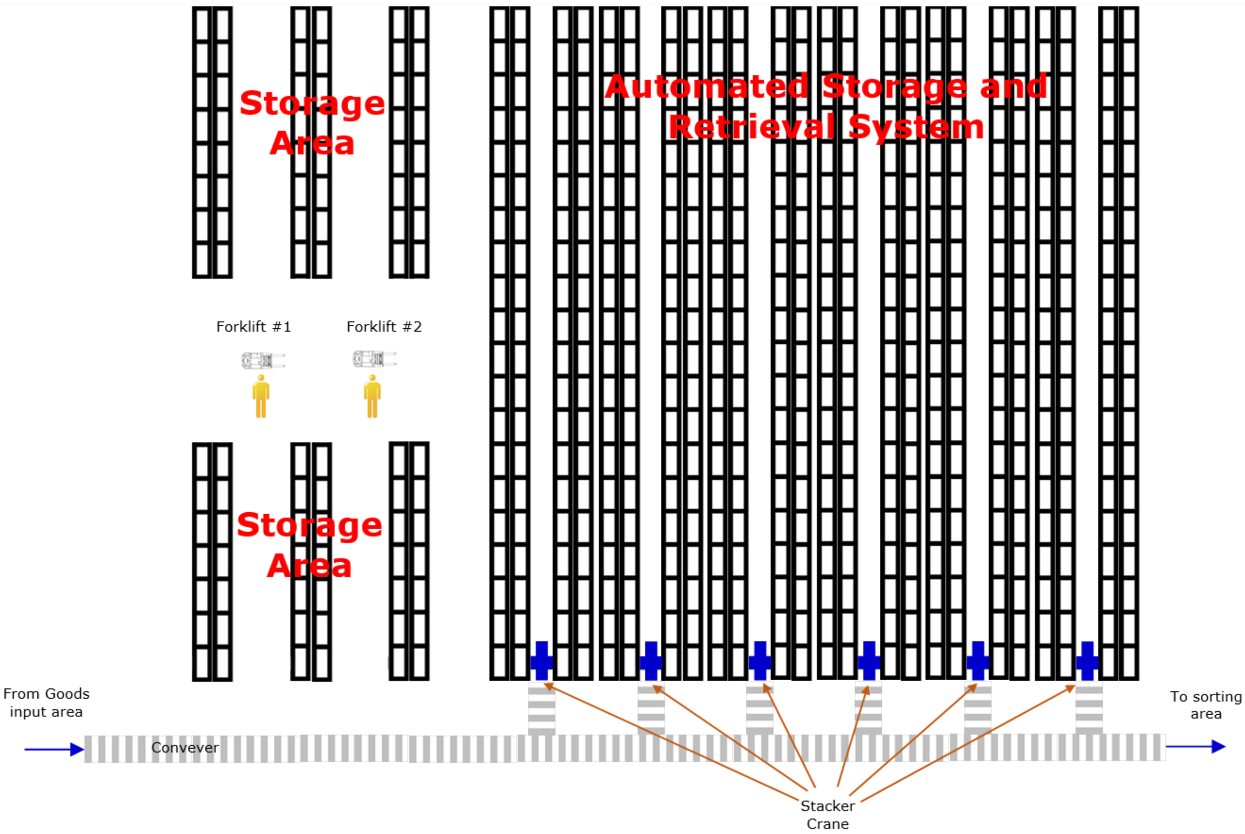
- Multi-shelf rack system (assumption)
  Area: 1000 m^2
  4 layers of shelf (1 meter high per layer)
  Total height 4 meter (consideration of lift height of forklift)
  500 pallets per layer
  Total 2,000 pallets
- ASRS (see 4.2.2.3 f))

- Consideration:
  - Storage capability
  - Storage method
  - Internal transportation
  - Links to other areas
  - Relative operation
- Data and parameters of CO_2 emissions

Name	Q'ty	Mode of CO_2 Emissions	Emission Factors	Activity Data	Note
Storage shelf	1	-	-	-	- Multi-shelf rack system - 1000 m^2 - No CO_2 Produced
Storage machine	1	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- ASRS - 5250 m^2 - Consideration: ● Running time ● Power ● Workload / Order quantity
Forklift	2	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- Consideration: ● working time
Conveyer	18*	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- 1 conveyer corresponds to 1 tunnel - 1 conveyer for internal transportation - Consideration: ● Length/Distance ● Power
Staff	2	Human mobility	Emissions weight/ Human activities	Average emissions per hour	- 2 forklift drivers - Consideration: ● Working time ● Workload

[*Table 4-4: Data and Parameters in Storage process*]

* Consideration:
7.62 meters length per unit (conveyer), assumption is 18 units within Goods Input.



[*Fig 4-8: Model of storage*]

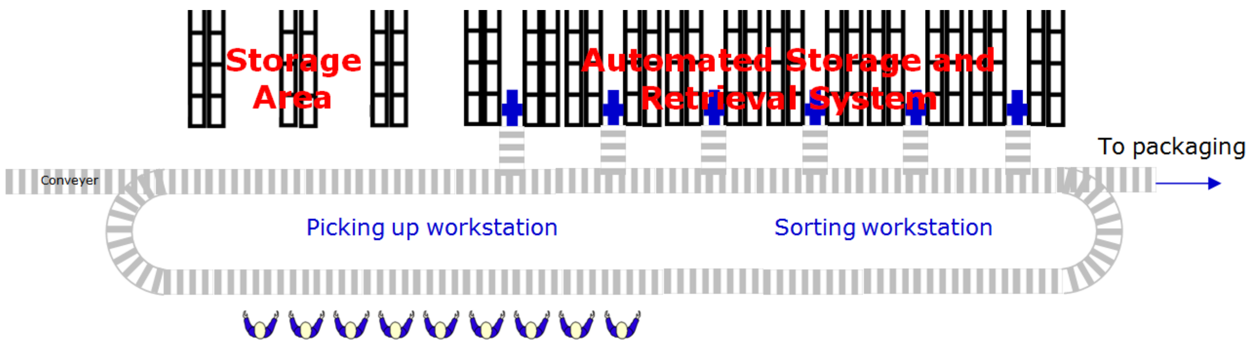
c) Picking up
Sending goods that required by customer is the basic function of a distribution center. So it is necessary activities to find and pick good up according to customer's order. There are also two methods to execute activities of finding and picking goods up. One is taken by staff from storage area, another is executed by ASRS. It should be noted that goods are in totes or on pallets in that moment, the correct goods required by customers need to be picked from totes or pallets and put into another totes for sending to customer. A loop conveyer is used to carry totes and pallets.

- Consideration:
  - Picking up method
  - Workload of staffs
  - Peak condition, for example, double than usual (according to season)
  - Internal transportation
  - Relative operation
- Data and parameters of CO_2 emissions

Name	Q'ty	Mode of CO_2 Emissions	Emission Factors	Activity Data	Note
Picking machine	1	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- ASRS - 5250 m^2 - Consideration: ● Running time ● Power ● Workload / Order quantity
Conveyer	9*	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- For internal transportation - Consideration: ● Length/Distance ● Power
Staff	9	Human mobility	Emissions weight/ Human activities	Average emissions per hour	Consideration: ● Working time ● Workload (average 96 totes per staff per day)

[*Table 4-5: Data and Parameters in Picking UP process*]

* Consideration:
7.62 meters length per unit (conveyer), assumption is 9 units within Goods Input.



[*Fig 4-9: Model of picking up*]

d) Sorting

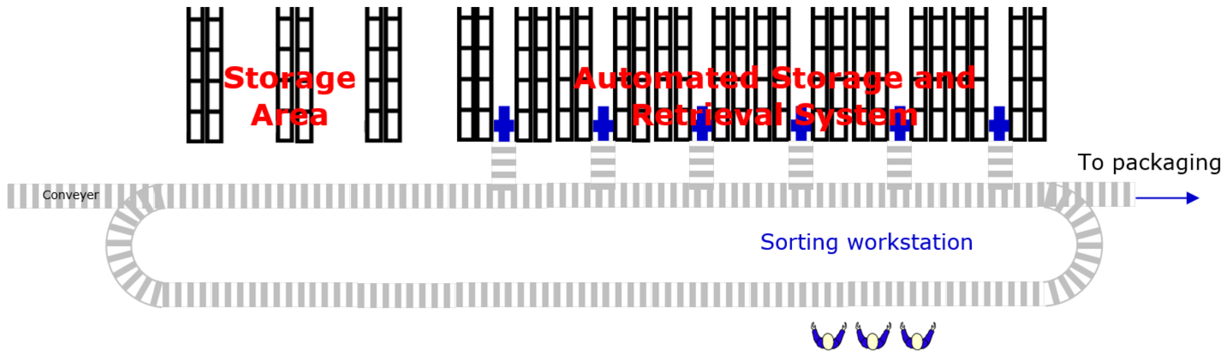
Relative to other processes, sorting goods is not a hard work but need more patience and careful. It needs not more machines and staffs. In this model, the workstation of sorting is considered to be located on the position near picking up workstation.

- Consideration:
  - Sorting method
  - Workload of staffs
  - Peak condition
  - Internal transportation
  - Relative operation
- Data and parameters of CO_2 emissions

Name	Q'ty	Mode of CO_2 Emissions	Emission Factors	Activity Data	Note
Conveyer	3*	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- Between Picking Up area and Packaging area - No other machines - Consideration: • Length/Distance • Power
Staff	3	Human mobility	Emissions weight/ Human activities	Average emissions per hour	Consideration: • Working time • Workload (average 288 totes per staff per day)

[*Table 4-6: Data and Parameters in Sorting process*]

* Consideration:
7.62 meters length per unit (conveyer), assumption is 3 units within Goods Input.



[*Fig 4-10: Model of sorting*]

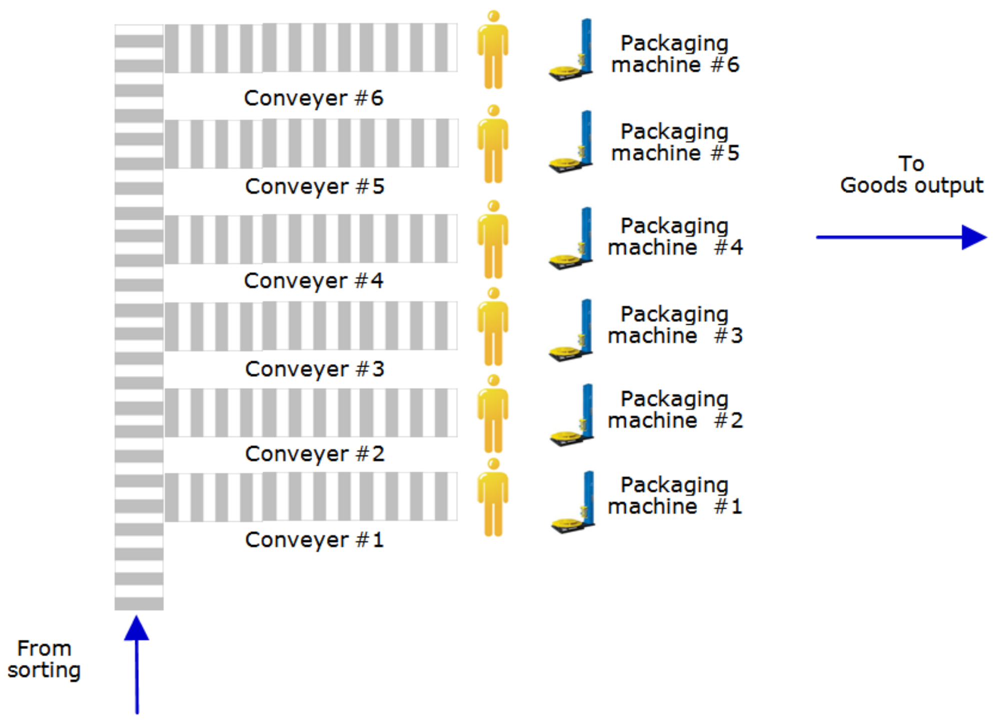
e) Packaging
Packaging is a work to pack the goods into a suitable box in order to send to customers. According to the analysis mentioned below, there are 6 packaging machines correspond to docks.

- Consideration:
  - Packaging method
  - Workload of staffs
  - Peak condition
  - Internal transportation
  - Relative operation
- Data and parameters of CO_2 emissions

Name	Q'ty	Mode of CO_2 Emissions	Emission Factors	Activity Data	Note
Packaging machine	6	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- 1 packaging machine corresponds to 1 dock - Consideration: ● Power ● Workload / Order quantity
Conveyers	12*	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- 1 conveyer corresponds to 1 packaging machine - Consideration: ● Length/Distance ● Power
Staffs	6	Human mobility	Emissions weight/ Human activities	Average emissions per hour	- 1 staff operates 1 packaging machine - Consideration: ● Working time ● Workload (average 96 totes per staff per day)

[*Table 4-7: Data and Parameters in Packaging process*]

* Consideration:
7.62 meters length per unit (conveyer), assumption is 12 units within Goods Input.

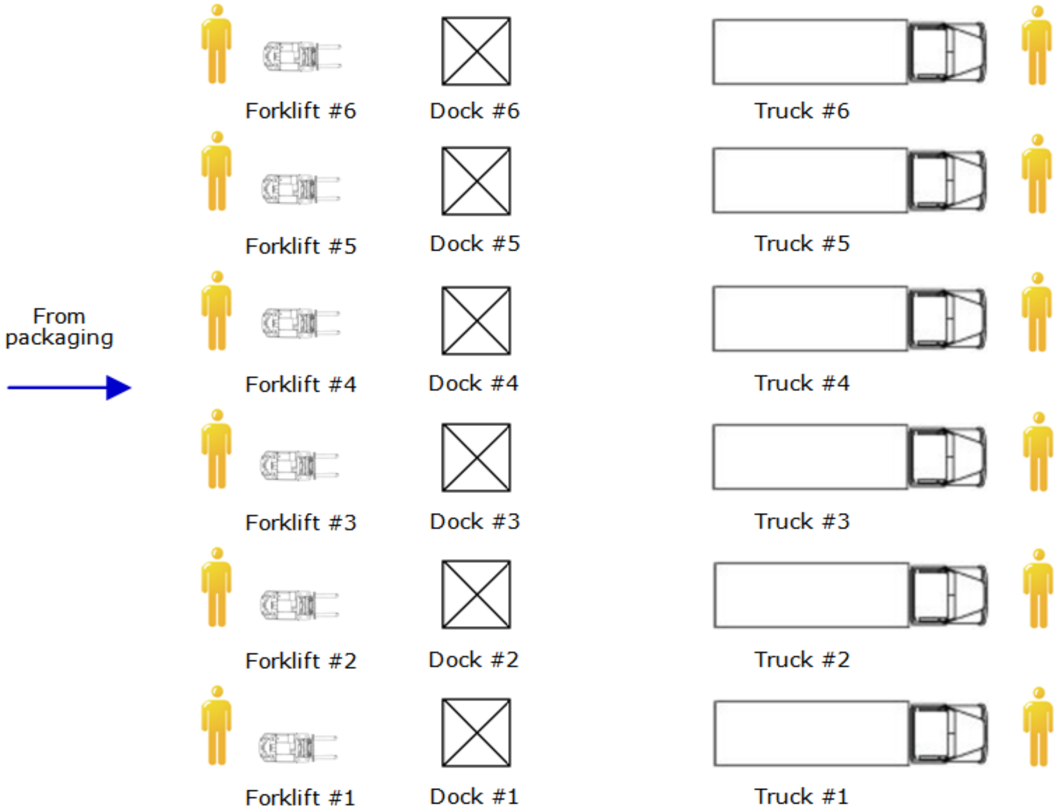


[*Fig 4-11: Model of packaging*]

f) Goods Output
According to the above throughput quantity, some values of outbound are calculated as follows:
   - 86.5 tones per week (52 weeks per year)
   - 17 trucks per week
   - 3.5 trucks per day (5 days per week)
- Consideration:
   - Peak condition, for example, double than usual (according to season)
   - Truck waiting time (according to loading speed)
   - Working time
   - Internal transportation
   - Different customers
   - Relative operation
- Data and parameters of CO_2 emissions

Name	Q'ty	Mode of CO_2 Emissions	Emission Factors	Activity Data	Note
Dock	6	-	-	-	- Maximum Status: 6 trucks loading goods at the same time - No CO_2 produced
Truck	6	Fuel consumption	Emissions weight/ Fuel consumption	Fuel consumption per 100 km (MPG)	- 1 truck corresponds to 1 dock - Consideration: ● Distance within system boundary
Forklift	6	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- 1 forklift corresponds to 1 dock - Consideration: ● working time
Staff	12	Human mobility	Emissions weight/ Human activities	Average emissions per hour	- 6 truck drivers and 6 forklift drivers - Consideration: ● Working time ● Workload

[*Table 4-8: Data and Parameters in Goods Input process*]



[*Fig 4-12: Model of goods output*]

g) Other consideration Data and parameters of CO_2 emissions

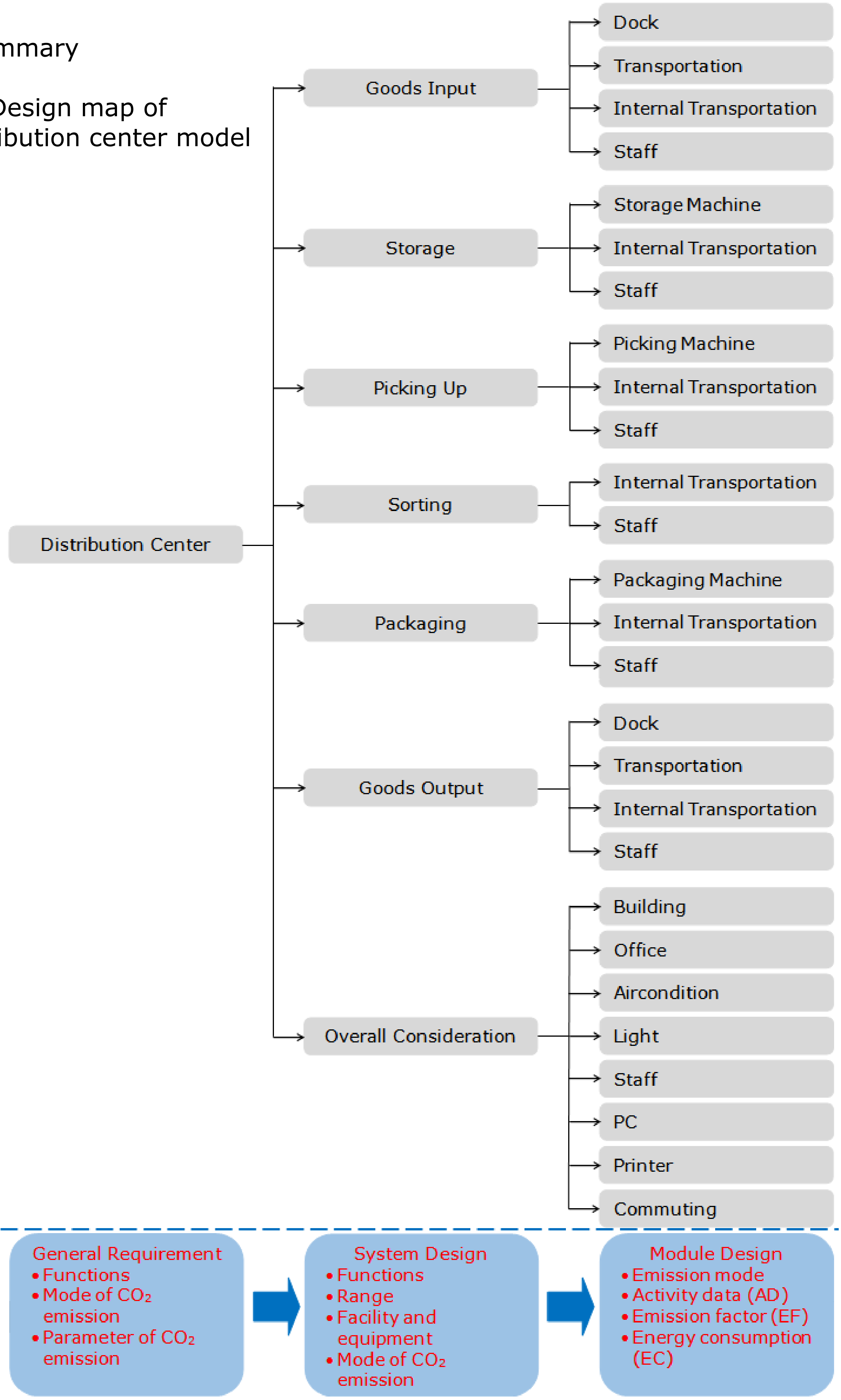
Name	Q'ty	Mode of CO_2 Emissions	Emission Factors	Activity Data	Note
Building	1	-	-	-	- Area: 10,500 m^2 - Length: 131.25 m - Width: 80 m - Height: 11.25 m (Assumption: 15 layers of shelf, 0.75 meters high per layer) - No CO_2 produced
Light	500	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- For whole building (Assumption: T5HO fluorescent [63] lamp, average illuminated area is 21 m^2 per lamp) - Consideration: • Working time • Power
Air conditions		Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- Central air condition - Consideration: • Working time • Power

Office	1	-	-	-	- Area: 100 m^2, includes: • Office area • Dining hall • etc. - No CO_2 produced
Staff	15	Human mobility	Emissions weight/ Human activities	Average emissions per hour	- Office staffs, include • Manager • Human Resource • Finance • Equipment maintenance • etc. - Consideration: • Working time • Workload
Personal computer	55	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- 1 unit for 1 staff - Consideration: • Working time • Power
Printer	20	Power consumption	Emissions weight/ Power consumption	Power consumption per hour	- Assumption: • 2 for office • 9 for ASRS and picking • 3 for sorting • 6 for packaging and goods output - Consideration: • Working time • Power
Commuting	55	Fuel consumption	Emissions weight/ Fuel consumption	Fuel consumption per 100 km (MPG)	- Assumption: • Every staff has a passenger car for commuting - Consideration: • Commuting distance • Types of passenger car

[*Table 4-9: Other Data and Parameters*]

4.2.3. Summary

4.2.3.1. Design map of distribution center model



[*Fig 4-13: Design map of distribution center-model*]

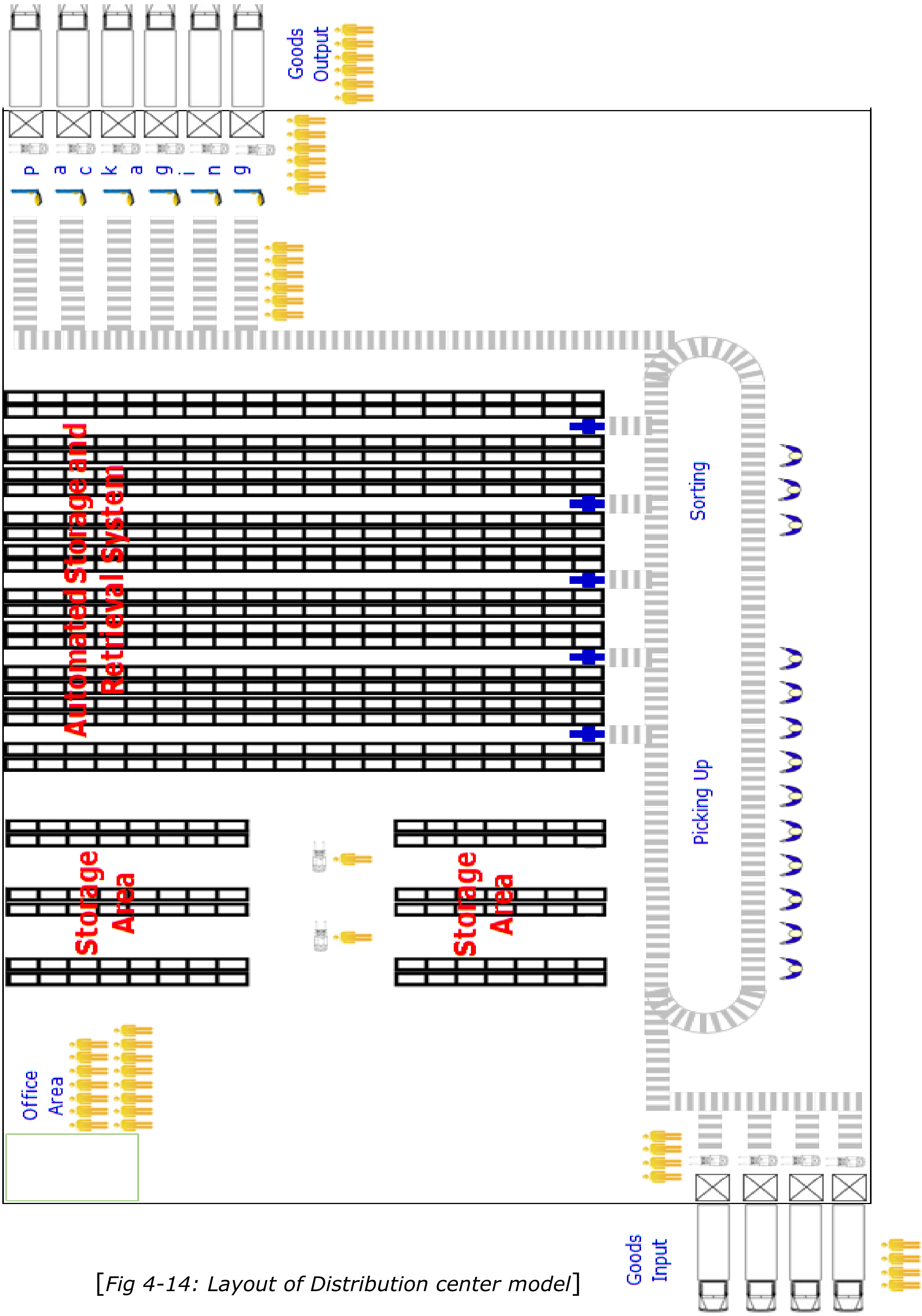
4.2.3.2. Data and parameters

Mark			
Mark	Mode of CO_2 Emissions	I	Power consumption
		II	Fuel consumption
		III	Human mobility
	Emission Factors	A	Emissions weight/Power consumption
		B	Emissions weight/Fuel consumption
		C	Emissions weight/Human activities
	Activity Data	1	Power consumption per hour
		2	Fuel consumption per 100 km (MPG)
		3	Average emissions per hour

General Requirement	System Design	Module Design				
		Component	Q'ty	Mode	Factor	Activity
Distribution Center • Functions • Mode of CO_2 emissions • Parameter of CO_2 emissions	Goods Input • Functions • Range • Facility • Emission Mode	Dock	4	-	-	-
		Truck	4	II	B	2
		Forklift	4	I	A	1
		Conveyer	8	I	A	1
		Staff	8	III	C	3
		PC	8	I	A	1
	Storage • Functions • Range • Facility and equipment • Emission Mode	Storage shelf	1	-	-	-
		Storage mach.	1	I	A	1
		Forklift	2	I	A	1
		Conveyer	18	I	A	1
		Staff	2	III	C	3
		PC	2	I	A	1
	Picking Up • Functions • Range • Facility • Emission Mode	Picking machine	1	I	A	1
		Conveyer	9	I	A	1
		Staff	9	III	C	3
		PC	9	I	A	1
		Printer	9	I	A	1
	Sorting • Functions • Range • Facility • Emission Mode	Conveyer	3	I	A	1
		Staff	3	III	C	3
		PC	3	I	A	1
		Printer	3	I	A	1
	Packaging • Functions • Range • Facility • Emission Mode	Packaging mach.	6	I	A	1
		Conveyers	12	I	A	1
		Staffs	6	III	C	3
		PC	6	I	A	1
		Printer	3	I	A	1
	Goods Output • Functions • Range • Facility • Emission Mode	Dock	6	-	-	-
		Truck	6	II	B	2
		Forklift	6	I	A	1
		Staff	12	III	C	3
		PC	12	I	A	1
		Printer	3	I	A	1
	Overall Consideration • Functions • Facility • Emission Mode	Building	10,500 m^2	-	-	-
		Throughput In.	4,500 *t/y*	-	-	-
		Throughput Out.	4,500 *t/y*	-	-	-
		Air condition	1 *set*	I	A	1
		Lights	500 *pcs*	I	A	1
		Office	100 m^2	-	-	-
		Staff	15	III	C	3
		PC	15	I	A	1
		Printer	2	I	A	1
		Commuting	55	II	B	2

[*Table 4-10: Data and parameters of Distribution center model*]

4.2.3.3. Layout example



[*Fig 4-14: Layout of Distribution center model*]

5. Calculation of CO_2 Footprint

Calculation of CO_2 footprint of distribution center is main target of this topic. As we known, calculating the carbon footprint is one of the important and effective way to assess greenhouse gas emissions. We have constructed a model of distribution center and defined some useful parameters. Next question is how to calculate. To solve this question, we should to choose an appropriate calculation approach at first, and then do the calculation to get the result.

5.1. Introduction to calculation approaches

There are many approaches to calculate carbon footprint (carbon emissions) in the world. Some national governments and international organizations (e.g. ISO, IPCC, and BSI [65]) issue their own calculation standards through a large number of researches of carbon emissions. After years of development, there has been some high awareness of carbon emissions calculation standards.

5.1.1. Introduction

Different countries or organizations have their own calculation approaches (or named standards) based on their comprehension and needs. In general, there are mainly two basic types to calculate carbon footprint, one is Input-Output (I-O) model based on input-output analysis, and other is Life cycle Assessment (LCA) model based on process analysis [65]. Many approaches/standards of calculation/assessment are derived from these two types. Except these two types, there are some other approaches can calculate carbon footprint, like System Modeling Language (SysML), though the approach of SysML is not a tradition and popular calculation approach of carbon footprint in the field of environment/climate study.

a) Input-Output (I-O)

An input-output model is a mathematical model studying the relationship of the inputs and outputs between various economic departments. It was first proposed by the famous American economist W. Leontief, and it is a more mature economic analysis.

Input-output approach is a bottom-up approach. Its prominent advantage is that it can use data provided by input-output tables to calculate the direct and indirect effects of economic changes to the environment, and get physical conversion relationship between the product and its material inputs [65]. Usually, this approach is used for calculation carbon footprint in macro-level. If the data in input-output tables is sufficient, then the calculation is simple.

Because the change of environment is dynamic, the data in input-output tables always becomes outdate. In order to get accurate calculation results, the data have to be update at any time. On the other hand, the calculation result is only a rough result because it ignores some variable factors, for example, possible difference of carbon emissions of the same product in different produce process, possible error of calculation when using the average processing method. Another disadvantage is that it can not get the result of single product because its result is a sum of carbon footprint of different products and processes.

b) Life cycle Assessment (LCA)

What is a Life Cycle (LC)?
Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal [65]

The whole life cycle of a product, a process or an event includes: extraction and processing of raw materials, manufacturing, transportation and sales, use, re-use, maintenance, recycling, until the final waste [66].

What is a Life Cycle Assessment (LCA)?
Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system [67]

Life cycle assessment is an approach for evaluating impact and potential impact on environment caused by all inputs and outputs of a product, service, process or activity during its whole life cycle. It is a traditional (from "cradle" to "grave") calculation methods [4].

Life cycle assessment approach is a top-down approach. Because of relative detailed and accurate calculating process, this approach is suitable for calculation of carbon footprint in micro-level.

For life cycle assessment, it is relative complex and difficult process to determine the life cycle of a product, service, process or activity. Similarly, determination of the boundary and different phases of life cycle is difficult and complex too.

A sample step of calculation as follows [68]:
- Establishing a manufacturing flow chart of the product
- Determining boundary of system
- Collecting data
- Calculating carbon footprint
- Checking the uncertainty

c) Brief introduction of approaches/standards
Based on two basic types, there are some approaches/standards issued by different organizations.

Basic types	Name of approaches	Organizations	Note
Input-Output	GHG Protocol	WRI/WBCSD	(1)The commonality of these approaches /standards is to provide a method for calculating the carbon footprint (2)Not all approaches /standards be listed
	ISO 14064:2006	ISO	
Life Cycle Assessment	PAS 2050:2011	BSI	
	ISO 14040/14044:2006	ISO	
	ISO/TS 14067:2013	ISO	
	TS Q0010:2009	METI [69]	
Combination	IPCC2006	IPCC	

[*Table 5-1: Summary and classification of calculation approaches of carbon footprint*]

- GHG Protocol [70]
The Greenhouse Gas Protocol (GHG Protocol) is the most widely used international accounting tool for government and business leaders to understand, quantify, and manage greenhouse gas emissions. The GHG Protocol, a decade-long partnership between WRI and WBCSD, is working with businesses, governments, and environmental groups around the world to build a new generation of credible and effective programs for tackling climate change.

It provides the accounting framework for nearly every GHG standard and program in the world - from the International Standards Organization to The Climate Registry - as well as hundreds of GHG inventories prepared by individual companies.

The GHG Protocol consists of four separate but linked standards:
- Corporate Accounting and Reporting Standards (Corporate Standard)
- Project Accounting Protocol and Guidelines
- Corporate Value Chain (Scope 3) Accounting and Reporting Standard
- Product Life Cycle Accounting and Reporting Standard

- ISO 14064:2006
The ISO 14064:2006 is part of the ISO 14000 series of International Standards for environmental management. As an international standard, it provides an unified mode of information and data management, reporting and verification of greenhouse gas. By using this standard can ensure greenhouse gas emissions quantification, monitoring, reporting and verification and validation of the consistency, transparency and credibility, and can guide governments, businesses,

regions and other organizations to measure and control greenhouse gas emissions, to promote the GHG emissions and carbon trading.

The Standard has three parts [71].

- ISO 14064-1:2006 includes requirements for the design, development, management, reporting and verification of an organization's GHG inventory.
- ISO 14064-2:2006 includes requirements for planning a GHG project, identifying and selecting GHG sources, sinks and reservoirs relevant to the project and baseline scenario, monitoring, quantifying, documenting and reporting GHG project performance and managing data quality.
- ISO 14064-3:2006 can be applied to organizational or GHG project quantification, including GHG quantification, monitoring and reporting carried out in accordance with ISO 14064-1 or ISO 14064-2.

- PAS 2050:2011

  PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. It compiled by the BSI, and aims to make clear regulations for evaluation requirements of greenhouse gas emissions during the life cycle of goods and services. This specification is not only helpful for organization or companies to manage carbon emissions of goods and services, but also can help organization or companies to find opportunities of reducing carbon emissions in the stages of product design, production, use, transport, etc.

  Evaluation methods used by this specification are based on the evaluation methods of ISO14040/14044 and formulated through clear assessment requirements of greenhouse gas emissions of goods and services within the life cycle. Therefore, they are basically consistent in determining the boundaries of emissions and emission factors. This specification gives clear regulations for system boundary determination, greenhouse gas emissions resources related to goods within the boundary, data required by complete analysis and calculation methods on aspects of business-to-business (B2B) and business-to-consumer (B2C).

- ISO 14040/14044 : 2006

  In 2006, ISO issued ISO14040:2006 Environmental management -- Life cycle assessment -- Principles and framework and ISO14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines. These two standards provision the assessment range of carbon emissions of product life cycle, determination of functional boundary and determination of baseline flow.

- ISO/TS 14067:2013 [72]
  In 2013, ISO issued ISO/TS 14067:2013 Greenhouse gases -- Carbon footprint of products -- Requirements and guidelines for quantification and communication.

  ISO/TS 14067:2013 specifies principles, requirements and guidelines for the quantification and communication of the carbon footprint of a product (CFP), based on International Standards on life cycle assessment (ISO 14040 and ISO 14044) for quantification and on environmental labels and declarations (ISO 14020, ISO 14024 and ISO 14025) for communication. Requirements and guidelines for the quantification and communication of a partial carbon footprint of a product (partial CFP) are also provided.

  ISO/TS 14067:2013 is applicable to CFP studies and different options for CFP communication based on the results of such studies. Where the results of a CFP study are reported according to ISO/TS 14067:2013, procedures are provided to support both transparency and credibility and also to allow for informed choices.

  ISO/TS 14067:2013 also provides for the development of CFP-product category rules (CFP-PCR), or the adoption of product category rules (PCR) that have been developed in accordance with ISO 14025 and that are consistent with ISO/TS 14067:2013.

- TS Q0010:2009
  TS Q0010 -General principles for the assessment and labeling of Carbon Footprint of Products is a carbon footprint labeling program promoted by METI. Calculation guidelines are given by METI, Japan Environmental Management Association for Industry (JEMAI) and Mizuho Research Institute. This standard is not widely used. In first phase of the pilot, only 30 companies and 62 commodities participated this project. The applicability and effectiveness of this standard remains to be seen.

- Other approaches/standards
  Except mentioned above, based on different studying areas there are also some calculation (assessment) approaches/standards of Carbon Footprint. For example, a common carbon footprint approach for dairy – The IDF guide to standard life cycle assessment methodology for dairy sector [73] used for the dairy cattle farming and dairy manufacturing sectors, ICAO [74] Carbon Emissions Calculator (Version 5) used for estimating the amount of carbon emissions (CO_2) generated by a passenger in a flight, and so on.

There are also some carbon footprint calculators on internet. These calculators are easy to use and usually used for calculation of personal and family. But the results are not accurate enough. Following are some calculators as examples:

http://www.dotree.com/CarbonFootprint/
http://www.footprintnetwork.org/de/index.php/gfn/page/calculators/
http://www.epa.gov/climatechange/ghgemissions/ind-calculator.html
http://www.carbonfootprint.com/calculator.aspx

a) IPCC2006
As we mentioned in chapter 1.6, IPCC2006 provides different solving ways for different countries and different fields. This is a relative complete calculation approach. It gives detailed analysis of emission principles through detailed and comprehensive consideration of almost all emission sources of greenhouse gas.

IPCC2006 provides a basic equation:

$$\text{Emissions} = \text{Activity Data} \bullet \text{Emission Factors.}$$

IPCC2006 also has its limitations, such as only suitable for analysis of closed isolated island system, and can't calculate implicit carbon emissions in consumer aspect.

b) System Modeling Language (SysML)
What is the System Modeling Language [75]?
The Systems Modeling Language is a general-purpose graphical modeling language for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures, and facilities. In particular, the language provides graphical representations with a semantic foundation for modeling system requirements, behavior, structure, and parametric, which is used to integrate with other engineering analysis models.

SysML is a graphical modeling language in response to the UML [76] for Systems Engineering RFP [77] developed by the OMG [78], INCOSE [79], and AP233 [80]. It tries to integrate advantages of comprehensive structured approach and object-oriented approach, in order to establish a unified modeling language for systems engineering architecture design. SysML supports model and data interchange via XML [81] Metadata Interchange (XMI®) and the evolving AP233 standard (in-process). It includes Semantics and Notation.
SysML is usually used for solving system engineering problem. In this topic, we can use its diagrams to construct a path for calculation.

5.1.2. Example of calculation

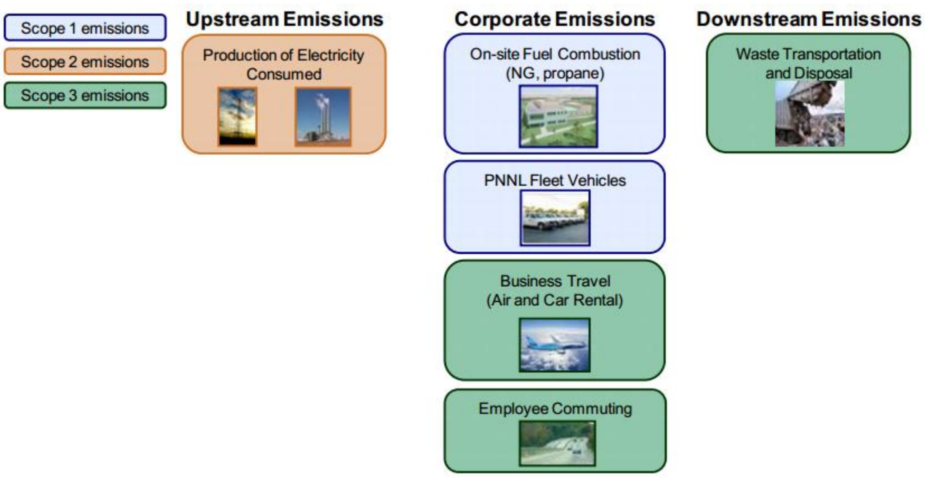
There are many examples of calculating carbon footprint. The simplest example is to calculate personal carbon emissions using a calculator of carbon emissions. We can get the result immediately after entering relevant data using those calculators. For an organization, like a factory or a university, the calculation of carbon footprint is more complex.

Following is an example of calculation processes of carbon footprint conducted by the Pacific Northwest National Laboratory (PNNL) in 2007 [82].

Step 1 Methodology

a) *Approaches*
   The Greenhouse Gas Protocol Corporate Accounting and Reporting Standard (GHG Protocol) was used as a basis for most CO_2 emissions calculations. This protocol includes Excel-based calculation tools which were customized. Alternative tools were incorporated to support the emissions calculations for which the GHG Protocol does not currently provide guidance.

b) *Boundaries*
   Establishing boundaries and scope of analysis is an important first step in designing an organization's carbon inventory.
   - *Operational Boundaries*
     PNNL's carbon emissions inventory includes facilities over which it has ownership and/or direct operational control and data available.
   - *Scope Boundaries*
     The GHG Protocol defines three categories of carbon emissions:
     - *Scope 1 – Direct emissions*
     - *Scope 2 – Electricity indirect emissions*
     - *Scope 3 – Other indirect emissions*



[*Fig 5-1: Scope of PNNL's carbon inventory*]

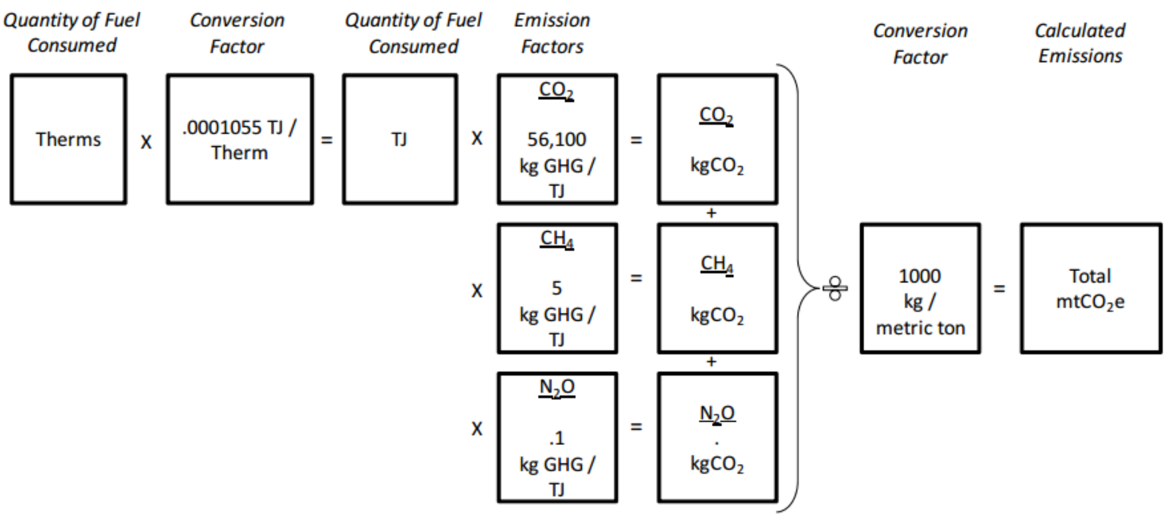
c) *Calendar year*
2007 was chosen as the base year for the first inventory.

d) *Data Collection and Calculation Methodology*
To calculate the emissions associated with all of PNNL's activities, a formula of activity data multiplied by an emission factor gave a total CO_2 equivalent number, usually expressed in metric tons of CO_2, as illustrated:

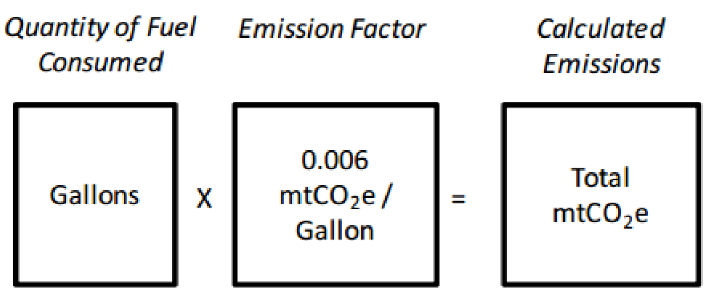
(Activity Data) X (Emission Factor) = GHG Emissions

A summary list of emission factors used in this analysis is provided.

- *Scope 1 – Direct Emissions from Fuel Use in Facilities*
  - *On-site Fuel Combustion*
    On-site fuel combustion at PNNL includes natural gas and propane. The emissions calculation for natural gas fuel and propane consumption is illustrated in following figure.

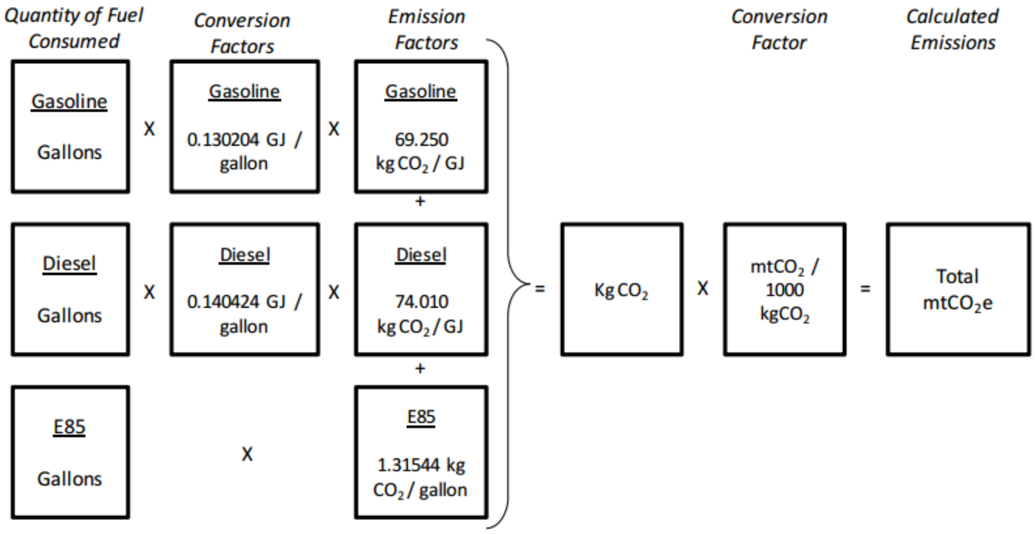


[*Fig 5-2: Method for calculating natural gas emissions*]



[*Fig 5-3: Method for calculating propane emissions*]

- *Fleet Vehicles*
  PNNL has a fleet vehicles, which are used for grounds maintenance, security, mobile laboratories, and other purposes. The emissions calculation for fleet vehicle fuel consumption for each of the three fuel types consumed is shown as below.



[*Fig 5-4: Method for calculating fleet vehicle emissions*]

- *Scope 2 – Indirect Emissions from Electricity Purchased*
  Scope 2 consist of purchased electricity and Renewable Energy Certificates (RECs).
  - *Purchased Electricity*
    PNNL consumed 90,365,048 kWh of electricity to support campus operations. Emission factors selected to calculate emissions associated with an organization's electricity consumption can vary significantly. The methodology underlying the Clean Air Cool Planet calculator for Scope 2 electricity emissions is illustrated in figure below.

Electricity Purchased	Transmission and Distribution Losses	Purchased Electricity Energy Content	Custom Fuel Mix	Source Energy Output	Source Generation Efficiency	Source Energy Input
Total kWh	9%	Total kWh X MMBtu/kWh	%	% of total fuel mix X Purchased electricity content = MMBtu	%	Energy Output / Generation efficiency = MMBtu

Cont.

2007 Fuel Mix (City of Richland)

Bio-mass	0.09%
Coal	2.57%
Cogeneration	0.00%
Geothermal	0.00%
Hydro	85.66%
Landfill Gases	0.00%
Natural Gas	1.06%
Nuclear	10.49%
Other	0.00%
Petroleum	0.03%
Total	100.00%

Coal	33%
Natural Gas	40%
Distillate Oil (#1-#4)	32%
Residual Oil (#5-#6)	32%
Nuclear	33%
Waste to Energy	22%
Hydro-Electric	34%
Wood Biomass	23%
Renewable (Wind, Solar)	34%

Source CO_2 Emissions Factor	Scope 2 CO_2 Emissions	Source CH_4 Emissions Factor	Scope 2 CH_4 Emissions	Source N_2O Emissions Factor	Scope 2 N_2O Emissions	Total Scope 2 Emissions
kg CO_2 / MMBtu	kg CO_2	kg / MMBtu	Source Energy Input X Source CH4 emissions factor = kg	kg / MMBTU	Source Energy Input X Source N20 emissions factor = kg eCO_2	kg CO2 + (kg eCO2 for CH4 X GWP)+ (kg eCO2 for N2O X GWP)= MT eCO_2

Coal	93.45
Natural Gas	52.76
Distillate Oil (#1-#4)	72.37
Residual Oil (#5-#6)	77.96
Nuclear	0.00
Waste to Energy	23.84
Hydro-Electric	0.00
Wood Biomass	0.00
Renewable (Wind, Solar)	0.00

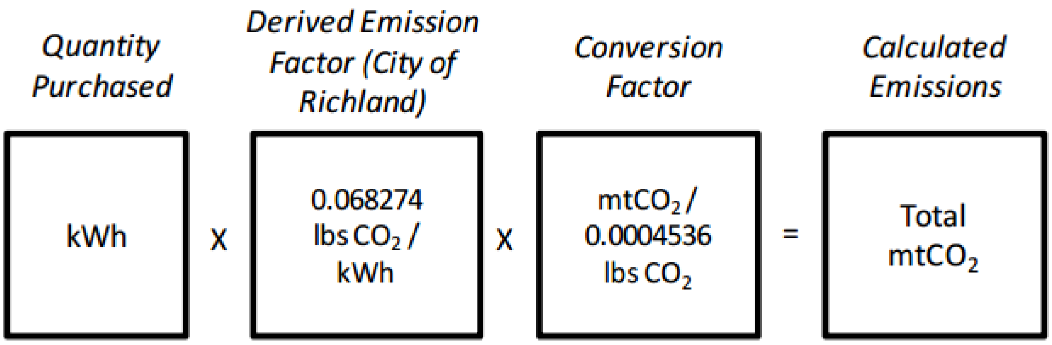
Coal	0.00106
Natural Gas	0.00106
Distillate Oil (#1-#4)	0.00317
Residual Oil (#5-#6)	0.00317
Nuclear	0.00000
Waste to Energy	0.00000
Hydro-Electric	0.00000
Wood Biomass	0.03165
Renewable (Wind, Solar)	0.00000

Coal	0.00158
Natural Gas	0.00011
Distillate Oil (#1-#4)	0.00148
Residual Oil (#5-#6)	0.00148
Nuclear	0.00000
Waste to Energy	0.11828
Hydro-Electric	0.00000
Wood Biomass	0.00422
Renewable (Wind, Solar)	0.00000

[*Fig 5-5: Method for calculating purchased electricity emissions*]

- *Renewable Energy Certificates (RECs)*
  A REC is a tradable commodity that represents proof that one megawatt-hour (MWh) of power is produced through an eligible renewable energy resource (e.g. wind, solar, geothermal). Because they represent electricity purchased from a renewable, non-carbon

emitting source, REC purchases reduce PNNL's net carbon emissions. The emissions reduction calculation for RECs is shown in figure below.



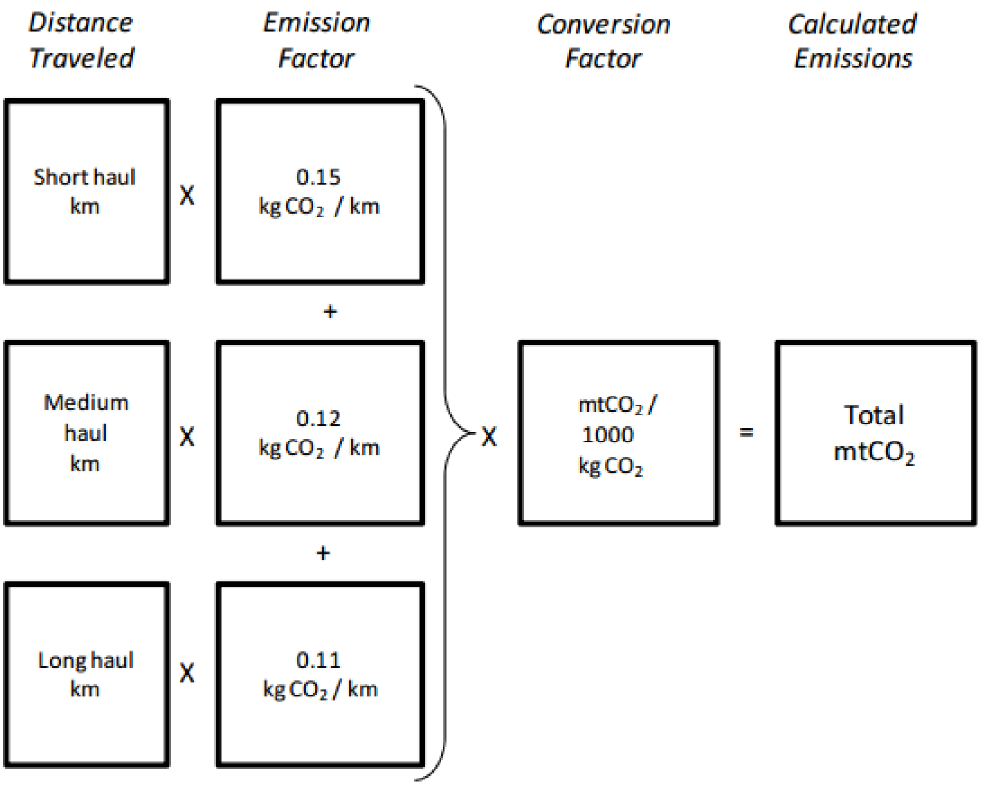
[Fig 5-6: Method for calculating REC emissions reduction]

- *Scope 3 – Other Indirect Emissions*

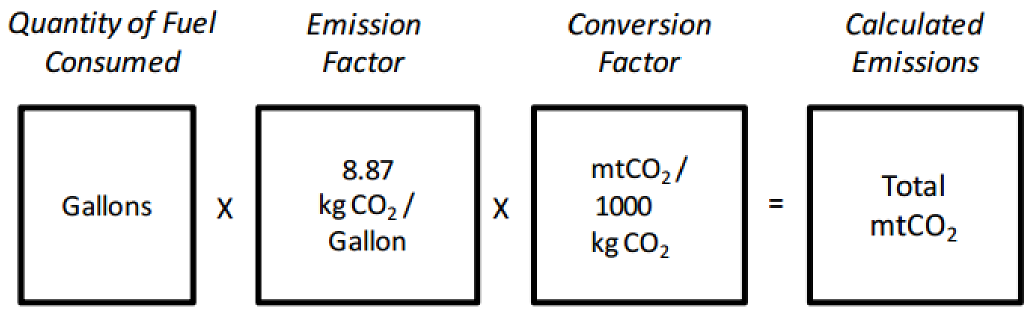
  Scope 3 emissions that were accounted for at PNNL included business travel, employee commuting, and waste disposal and transportation.

  - *Business Travel*

    Business Travel includes air travel and rental car travel. The emission calculation for business travel is shown in figure below.

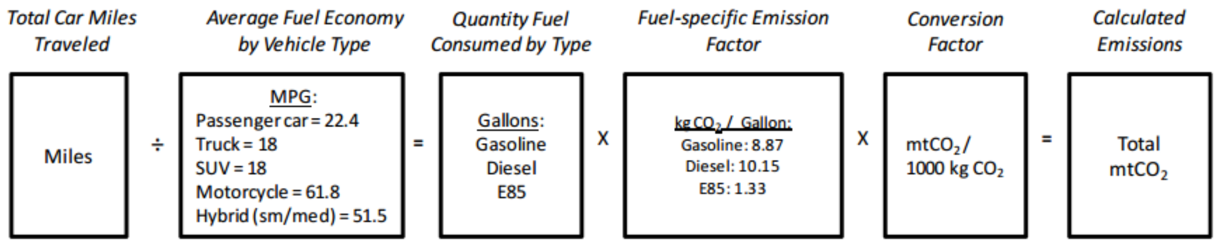


[Fig 5-7: Method for calculating emissions from air business travel]



[*Fig 5-8: Method for calculating emissions from business travel in rental cars*]

- *Employee Commuting*
  The emissions calculation for employee commute by automobile is shown in following figure.



[*Fig 5-9: Method for calculating employee commutes emissions*]

- Waste *Management*
  PNNL wanted to account for emissions associated with waste management and recycling to make this analysis as comprehensive as possible. But the GHG Protocol does not provide a method or tool to support such analysis. So PNNL included emissions associated with waste disposal and transportation only, and did not include avoided emissions from recycling and composting.

Step 2 Analysis and Results

a) *Emissions* Calculations
PNNL's total net CO_2 emissions for 2007 are presented in following table. Net CO_2 emissions represent the sum of emissions from Scope 1, 2 and 3 sources less the emissions savings associated with purchases of "green power" or RECS.

Category of Emissions	2007 CO_2 Emissions (metric tons)	% of Total Emissions	Description
Scope 1: Direct	8,716	24%	Natural Gas/Propane Consumption
	446	1%	Fleet Vehicles
Subtotal	**9,163**		
Scope 2: Indirect from Purchased Electricity	2,801	8%	Consumption of Purchased Electricity
	(339)		*REC Purchases*
Subtotal	**2,462**		
Scope 3: Other Indirect Emissions	14,441	40%	Business Travel
	7,657	25%	Employee Commuting
	786	2%	Solid Waste Disposal
Subtotal			
Total CO_2 Emissions	**22,884**		
Net CO_2 Emissions	**34,848**		

[*Table 5-2: PNNL 2007 CO_2 emissions*]

b) Lessons Learned about the Inventory Process
- *Improve data collection and data management process*
- *Seek additional calculation tools*
- *Conduct analysis by building and/or organizational unit*
- *Expand organizational boundaries*

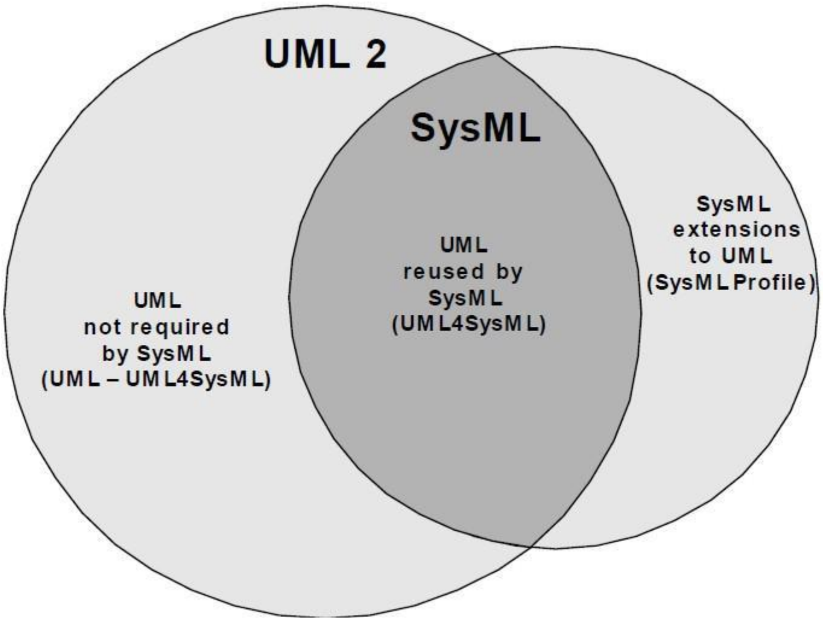
5.2. Calculation approach definition (SysML)

Relatively, a distribution center is not a complex system. After delimitation and definition, we have simplified system and constructed a model of distribution center. In the process of model construction, we have assumed and calculated some parameters, like building area, number of staffs, and so on. We have also defined the calculation equation in chapter 4. The next question is approach of calculation.

As a system, a distribution center can be analyzed with a system concept. For calculation of carbon footprint, we can also use system concept to construct an approach. In the aspect of solving engineering problems, system modeling language (SysML) is a widely used and better solution, and then it can be considered as a basis to construct an approach of calculation.

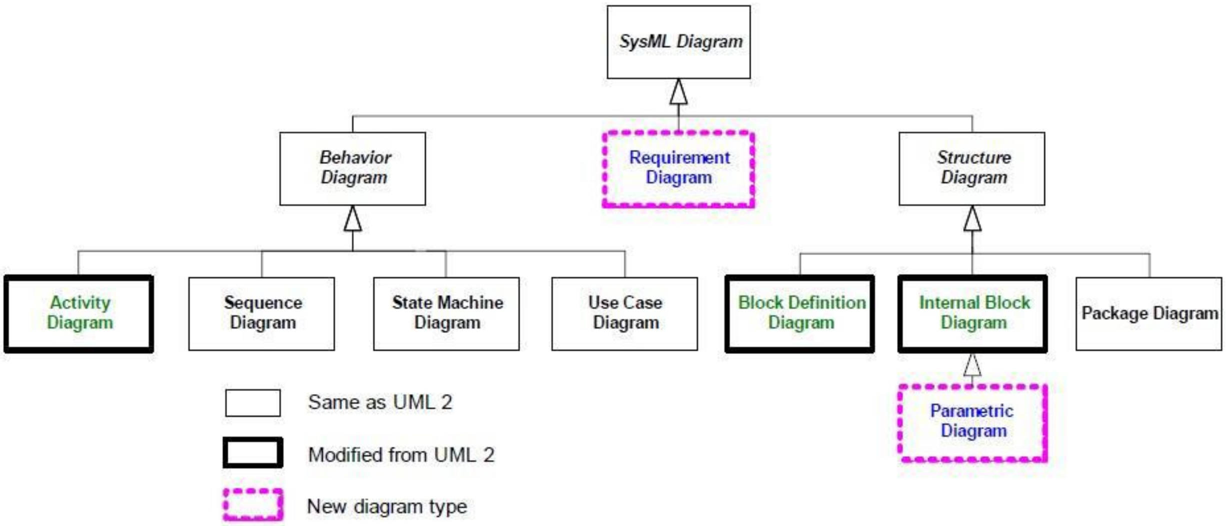
5.2.1. Brief of SysML

As mentioned before, SysML is a general-purpose graphical modeling language. It is an UML Profile that represents a subset of UML 2 with extensions [83].



[*Fig 5-10: Relationship Between SysML and UML*] [83]

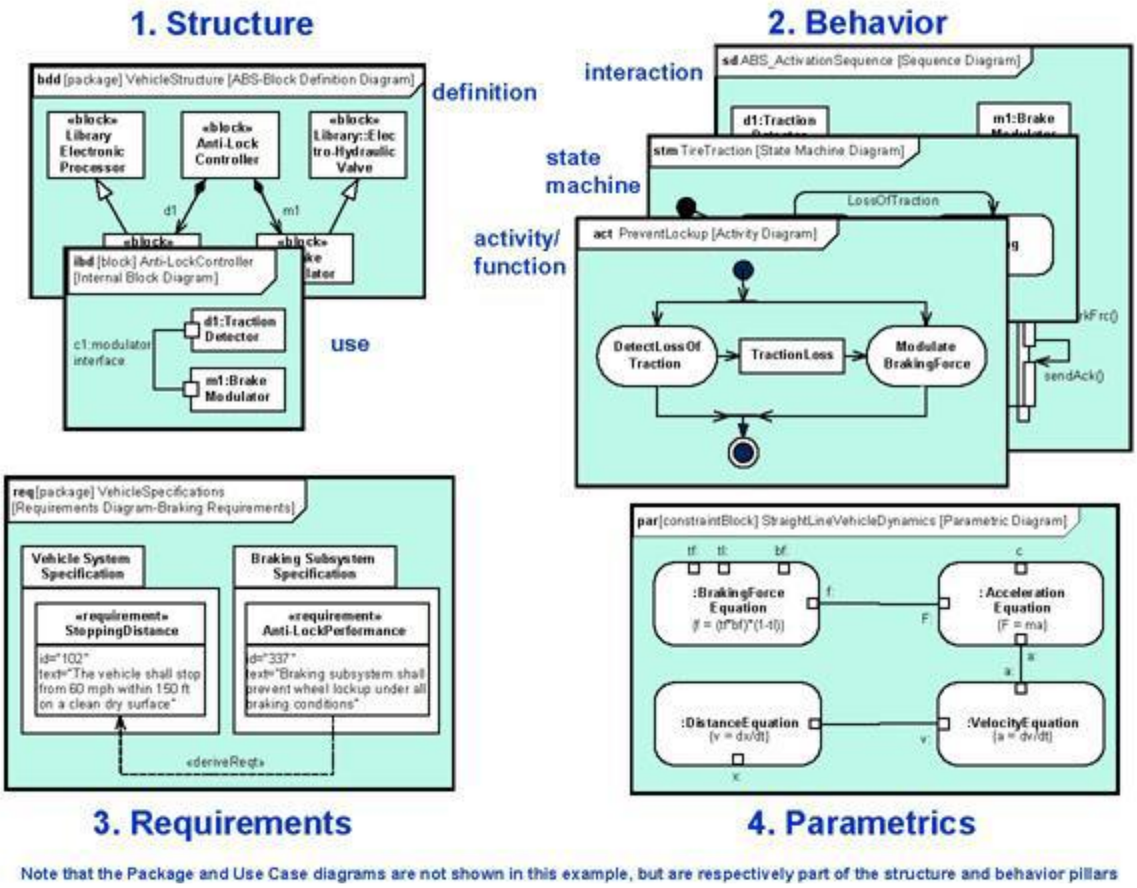
The SysML diagram types are identified in following figure.



[*Fig 5-11: SysML Diagrams*] [83]

The block is the basic unit of structure in SysML and can be used to represent hardware, software, facilities, personnel, or any other system element.

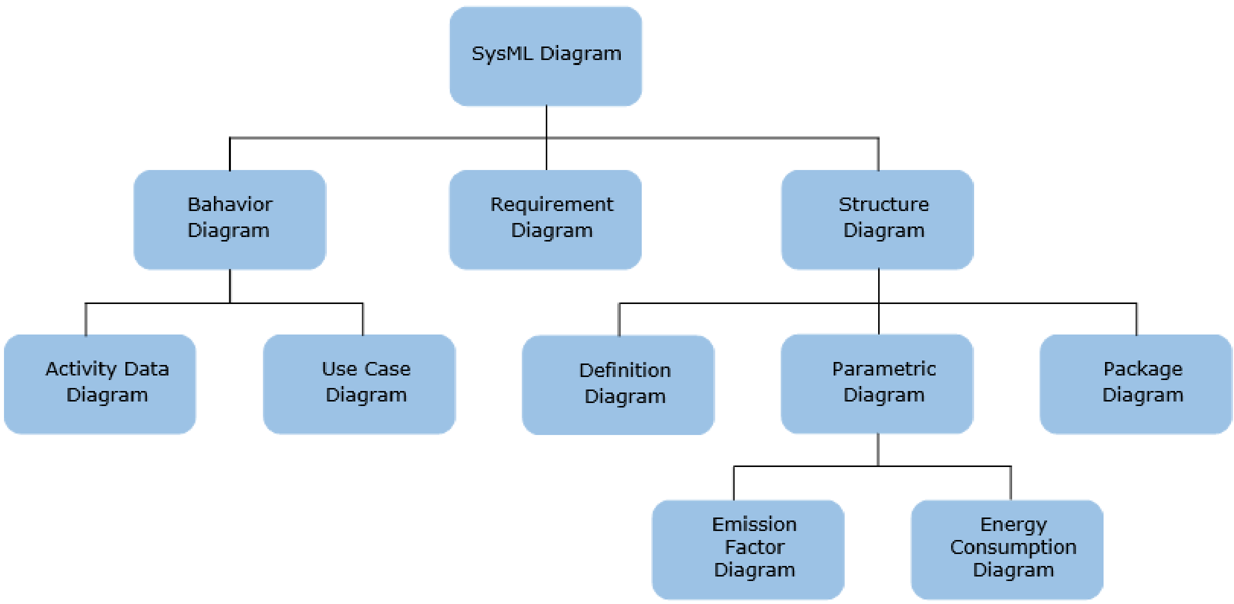
Pillars of SysML are shown in following figure.



[*Fig 5-12: Pillars of SysML*] [83]

5.2.2. Approach definition

Following figure shows the diagram of approach.



[*Fig 5-13: Approach Diagram*]

a) Blocks

In above figure, some blocks have done already in former chapter, like "requirement", "use case", and so on. Before the calculation, blocks "Activity Data", "Emission Factor" and "Energy Consumption" should be got.

Name of block	Status	note
Requirement	Completed	Chapter 4.2.2.
Activity Data	Open	
Use case	Completed	Chapter 5.1.2.
Definition	Open	Chapter 5.2.2.
Package	Completed	Chapter 4 and 5
Emission Factors	Open	
Energy consumption	Open	

[*Table 5-3: Analysis of block status*]

b) Steps

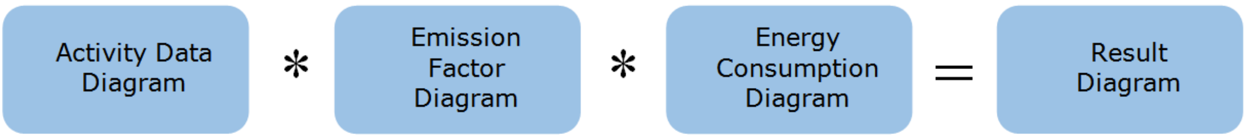
Basic equation

$$\text{Emissions} = \text{AD} \bullet \text{EF} \bullet \text{EC}$$

AD: Activity Data, information on the extent to which a human activity takes place

EF: Emission Factors, coefficients which quantify the emissions or removals per unit activity

EC: Energy consumption



[*Fig 5-14: Representation of equation*]

Step 1: Activity Data

To get activity data like Fuel consumption per 100 km (trucks), Power consumption per hour (lights), we can assume relevant parameters through investigation and calculation. Additionally, power of electrical equipment/devices is an important parameter.

Step 2: Emission Factor

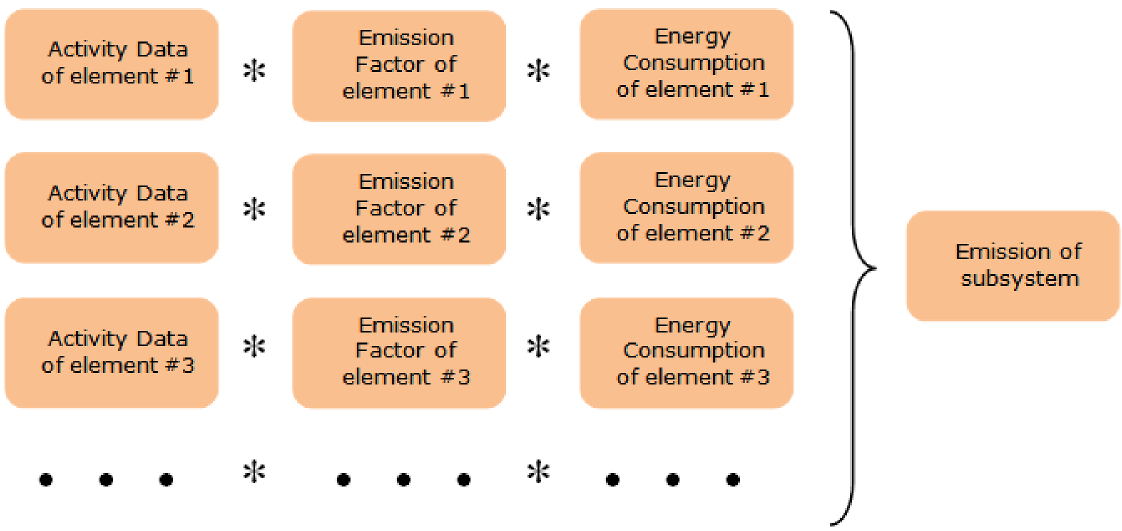
Obtain of emission factors (Emissions weight/Fuel consumption, Emissions weight/Power consumption, etc.) is a complex process. It has to consider types of emission sources, life cycle, used in which process, and so on. In this topic, the focus is calculation of carbon emissions, so the processes of obtain of emission factors will not be discussed. Additionally, there are many standards /approaches provide relevant emission factors. We can reference to these standards/approaches.

Step 3: Energy Consumption
Get the relevant parameters (following table) and data of energy consumption, like fuel consumption, Power consumption.

Elements	Relevant parameters		
Truck	Quantity	Transportation distance	
Forklift	Quantity	Power	Running time
Conveyer	Quantity	Power	Running time
ASRS		Power	Running time
Packaging machine	Quantity	Power	Running time
Lights		Power	Running time
Air condition	Quantity	Power	Running time
Office equipment	Quantity	Power	Running time
Staff	Quantity	working time	
Commuting	Quantity	Commuting distance	

[*Table 5-4: relevant parameters of energy consumption*]

Step 4: Calculation of subsystems
In subsystems (goods input, storage, picking up, sorting, packaging, goods output), calculating carbon emissions of elements and get the subtotal carbon emissions of subsystems.



[*Fig 5-15: Calculation of subsystems*]

Step 5: Calculation of elements that considered in overall
Calculating carbon emissions of elements that considered in overall, such as lights, office, and so on.

Step 6: Calculation of system
Sum of values in step 5 and step 6.

c) Supplement
- Emission factors in different standards will influence the result of calculation, so choosing an appropriate emission factor for relevant processes or elements is very important.
- In this topic, direct emissions include fuel consumption of trucks and human mobility, and do not include employee commuting and traveling.
- In this topic, indirect emissions mainly are consumption of electric power, and do not include consumption of water and discard of waste.

5.3. Calculation

In this topic, the period of calculation of carbon footprint is 1 calendar year. Normally, composition of a calendar year as follows:

Working time: 8 hours per week [84]
Weeks per year: 52.14
Weekend days per year: 104
Public holidays per year: 17 [84]
Annual leave days of per year: 30 (5 weeks, include Saturday) [84]
Days of 1 year: 365
Workdays of 1 year: 219
(Days of 1 year - Weekend days- Public holidays- Annual leave days)

5.3.1. Parametric Diagram

Step 1: Activity Data

Element	Emission Mode	Activity Data		Note
		Unit	Value	
Truck	Fuel consumption	*Liters / 100 km*	23.52	- Diesel - 4.2.2.3.b)
Forklift	Power consumption	*kW*	6.4	- 4.2.2.3.c)
Conveyer	Power consumption	*kW*	0.373	- 1 unit - 4.2.2.3.c)
ASRS	Power consumption	*kW*	118.8	* - 4.2.2.3.f)
Packaging mach.	Power consumption	*kW*	0.93	- Total power - 4.2.2.3.g)
Lights	Power consumption	*W*	60	* *
Air Condition	Power consumption	*kW*	336	- 4.2.2.3.h)
PC	Power consumption	*W*	60	- 4.2.2.3.i)
Printer	Power consumption	*W*	110	- 4.2.2.3.j)
Staff	Human mobility	*m^3/h*	0.08	***
Commuting	Fuel consumption	*Liters / 100 km*	5.8	- Gasoline - 4.2.2.3.L)

[*Table 5-5: Activity Data Matrix*]

* Quantity of stacker cranes is 17 units. Additionally, the power of overall control circuit is 10 kW. Total power of ASRS is 118.8 kW. ASRS includes storage function and picking up function.

** The power of "T5HO fluorescent" is 54 Watts. When using this lamp, other power (e.g. ballast) should be considered. According to reference article "Design guide for Warehouse – T5HO fluorescent", average power per lamp is 60 Watts (includes ballast).

*** There are many different data about on internet. Usually the average data 0.9kg / 1.0 kg carbon emissions per day per person is used to calculate an approximation of emission. For getting more detailed analysis, the emission data from the engineering toolbox is used for this topic [85]. Assumption is light work, and hosen data is 0.08 *m^3/h.*

Activity	Respiration per Person *(m^3/h)*	Carbon Dioxide Emissions per Person *(m^3/h)*
Sleep	0.3	0.013
Resting or low activity work	0.5	0.02
Normal work	**2 - 3**	**0.08 - 0.13**
Hard work	7 - 8	0.33 - 0.38

[*Table 5-6: Carbon Dioxide Emissions of Respiration*]

Step 2: Emission Factor

There are 3 emission modes in distribution center, i.e. fuel consumption, power consumption and human mobility.

a) Fuel consumption
For the concept of carbon footprint, the emissions not only include CO_2, but also includes greenhouse gas, like CH_4, N_2O, and so on. Relative to the emissions of CO_2, the emissions of other greenhouse gases is very small. For example, the emission factor of CH_4 is 85 mg/km and equal about 0.0003614 kg/Liter. So in this topic, the carbon emissions of other greenhouse gases will be not discussed.

Diesel

- Road transport default CO_2 emissions factors (IPCC2006, Chapter 1 Volume 2 , table 1.4): 74,100 *kg/TJ*
- Default net calorific values (NCVs) of CO_2 (IPCC2006, Chapter 1 Volume 2 , table 1.2):43.0 *TJ/Gg* (= 0.000043 *TJ/kg*)
- Density of diesel (table A3.8): 843.9 kg/m^3 [86] (= 0.8439 *kg/liter*)

Emission factors:

$EF_{Fuel,D}$ = 74,100 (*kg/TJ*) * 0.000043 (*TJ/kg*) * 0.8439 (*kg/liter*)
= 2.689 *kg/liter*

Gasoline

- Road transport default CO_2 emissions factors (IPCC2006, Chapter 1 Volume 2 , table 1.4): 69,300 *kg/TJ*
- Default net calorific values (NCVs) of CO_2 (IPCC2006, Chapter 1 Volume 2 , table 1.2):44.3 *TJ/Gg* (= 0.0000443 *TJ/kg*)
- Density of diesel (table A3.8): 740.7 kg/m^3 [86] (= 0.7407 *kg/liter*)

Emission factors:

$EF_{Fue,Gl}$ = 69,300 (*kg/TJ*) * 0.0000443 (*TJ/kg*) * 0.7407 (*kg/liter*)
= 2.274 *kg/liter*

b) Power consumption

Distribution center do not generate electrical power. It has to purchase electricity from market (named purchased electricity). Electricity is generated by several types, like hydropower, thermal power, wind power, nuclear power, and so on. For different types of electrical power generation, emission factors of electrical power are difference significantly. In this topic, because the location of distribution center is not specific, then it is difficult to analyze the purchased electricity generated by which types. An average electricity mission factor is used for distribution center [87].

Emission factors:

EF_{power} = 0.455 *kg/kWh*

c) Human mobility

Conversion of volume and weight

$$EF_{Human} = \frac{0.044\ (kg/mol)}{0.0224 (m^3/mol)} = 1.964\ kg/m^3$$

Emission Mode	Emission Factor		Note
	Unit	Value	
Fuel consumption	*Kg/Liter fuel*	2.689	$EF_{Fuel,D}$
	Kg/Liter fuel	2.274	$EF_{Fuel,G}$
Power consumption	*Kg/kWh*	0.455	EF_{power}
Human mobility	*Kg/m^3*	1.964	EF_{Human}

[*Table 5-7: Emission Factor Matrix*]

Step 3: Energy consumption

a) Truck
According to the definition of system boundary, transportation in this topic means trucks moving within precincts of distribution center. It is a short distance.
Assumed distance is average 1 km per truck per day (includes all moving activities within precincts of distribution center).

b) Forklift
Normally, utilization of forklift is not high. The data got form different channels of statistics or investigation is difference significantly.
In this topic, we select one of them: average 5 hours per day per forklift (forklifts are operated 250 days and 1,235 hours a year) [88].

c) Conveyer
Though intermittent working mode is a popular mode and can reduce energy consumption. But for a distribution center with busy business, waiting (conveyer doesn't work) time is not long. In this topic, continuous working mode is assumed.
Running time: 8 hours per day

d) ASRS
Based on the similar reason with c), ASRS works in continuous mode.
Running time: 8 hours per day

e) Packaging machine
Diversity of customer orders led to the final weight of packaging pallets are not the same. We cannot calculate the number of final pallets. At the same time, there is not any data to support running time of packaging machine.
Assumption is 200 kg per final pallet (one third of maximum load capacity of pallet), and 3420 kg goods per day per machine. Then the number of final pallet is 18. Assumed running time for packaging one pallet is 10 minutes according to experience.
Running time: 3 hours per day

f) Lights
All lights must be turned on during working time (include rest time at noon: 1 hour). For safety reason, assumed one tenth of lights must be turned on outside of working time.
Running time #1: 9 hours per day
Running time #2: 24 hours per day

g) Air condition
In the model of distribution center, the types of goods are not be specified.
Running time: 1219 hours per year (according to the area of building and power of air condition) [89]

h) PC (Personal Computer)
Assumption is that PC works continuously during working time.
Running time: 8 hours per day

i) Printer
Many experts believe that the utilization over 60% is a good status. According to a report studied by InfoTrends Company, the print devices worked more than 30 hours per week [90].
Assumption is that PC works in a good status during working time.
Running time: 6 hours per day

j) Staff
A staff stays in distribution center more than 8 hours because there is usually a rest time for lunch at noon. The rest time at noon is 1 hour. During the rest time, assumption is that all equipment (except lights and air condition) in stop status.
Working time: 9 hours per day (include rest time)

k) Commuting
Commuting distance: 22 km (single, 13.7miles) [91]

Element	Energy Consumption			Note
	Parameter	Unit	Value	
Truck	Distance	*km*	1	per day
Forklift	Running time	*hour*	5	per day
Conveyer	Running time	*hour*	8	per day
ASRS	Running time	*hour*	8	per day
Packaging mach.	Running time	*hour*	3	per day
Lights	Running time #1	*hour*	9	per day
	Running time #2	*hour*	24	per day
Air Condition	Running time	*hour*	1219	per year
PC	Running time	*hour*	8	per day
Printer	Running time	*hour*	6	per day
Staff	Working time	*hour*	9	per day
Commuting	Distance	*km*	44	per day

[*Table 5-8: Energy Consumption Matrix*]

5.3.2. Calculation result

Step 4: Calculation of subsystems

a) Goods Input

Element	Emission Mode	Quantity (A)	Activity Data (B)	Emission Factor (C)	Energy Consumption (D)	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)
Dock	-	4	-	-	-	-	-
Truck	Fuel Consumption	4	23.52 *L/100km*	2.689 *Kg/L*	1 *km*	2.530	0.554
Forklift	Power Consumption	4	6.4 kW	0.455 *Kg/kWh*	5 *hours*	58.240	12.755
Conveyer	Power Consumption	8	0.373 kW	0.455 *Kg/kWh*	8 *hours*	10.862	2.379
Staff	Human mobility	8	0.08 *m^3/h*	1.964 *Kg/m^3*	9 *hours*	11.313	2.477
PC	Power Consumption	8	60 *W*	0.455 *Kg/kWh*	8 *hours*	1.747	0.383
Subtotal	-	-	-	-	-	84.691	18.547

[*Table 5-9: Carbon emissions of Goods Input*]

b) Storage

Element	Emission Mode	Quantity (A)	Activity Data (B)	Emission Factor (C)	Energy Consumption (D)	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)
Storage shelf	-	1	-	-	-	-	-
Storage mach.	Power Consumption	1	118.8 *kW*	0.455 *Kg/kWh*	8 *hours*	*	*
Forklift	Power Consumption	2	6.4 kW	0.455 *Kg/kWh*	5 *hours*	29.120	6.377
Conveyer	Power Consumption	18	0.373 *kW*	0.455 *Kg/kWh*	8 *hours*	24.439	5.352
Staff	Human mobility	2	0.08 *m^3/h*	1.964 *Kg/m^3*	9 *hours*	2.828	0.619
PC	Power Consumption	2	60 *W*	0.455 *Kg/kWh*	8 *hours*	0.437	0.096
Subtotal	-	-	-	-	-	56.824	12.444

[*Table 5-10: Carbon emissions of Storage*]

* Storage machine is a part of ASRS in this topic. To avoid repeat calculation, carbon emissions of storage machine does not be calculated independently, and will be calculated in next subsystem.

c) Picking Up

Element	Emission Mode	Quantity (A)	Activity Data (B)	Emission Factor (C)	Energy Consumption (D)	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)
Picking machine*	Power Consumption	1	118.8 *kW*	0.455 *Kg/kWh*	8 *hours*	432.432	94.703
Conveyer	Power Consumption	9	0.373 *kW*	0.455 *Kg/kWh*	8 *hours*	12.219	2.676
Staff	Human mobility	9	0.08 *m^3/h*	1.964 *Kg/m^3*	9 *hours*	12.727	2.787
PC	Power Consumption	9	60 *W*	0.455 *Kg/kWh*	8 *hours*	1.966	0.430
Printer	Power Consumption	9	110 *W*	0.455 *Kg/kWh*	6 *hours*	2.703	0.592
Subtotal	-	-	-	-	-	462.047	101.188

[*Table 5-11: Carbon emissions of Picking Up*]

* Picking machine is a part of ASRS too. Here carbon emissions of picking machine include overall ASRS.

d) Sorting

Element	Emission Mode	Quantity (A)	Activity Data (B)	Emission Factor (C)	Energy Consumption (D)	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)
Conveyer	Power Consumption	3	0.373 *kW*	0.455 *Kg/kWh*	8 *hours*	4.073	0.892
Staff	Human mobility	3	0.08 *m^3/h*	1.964 *Kg/m^3*	9 *hours*	4.242	0.929
PC	Power Consumption	3	60 *W*	0.455 *Kg/kWh*	8 *hours*	0.655	0.143
Printer	Power Consumption	3	110 *W*	0.455 *Kg/kWh*	6 *hours*	0.901	0.197
Subtotal	-	-	-	-	-	9.872	2.162

[*Table 5-12: Carbon emissions of Sorting*]

e) Packaging

Element	Emission Mode	Quantity (A)	Activity Data (B)	Emission Factor (C)	Energy Consumption (D)	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)
Packaging mach.	Power Consumption	6	0.93 *kW*	0.455 *Kg/kWh*	3 *hours*	7.617	1.668
Conveyer	Power Consumption	12	0.373 *kW*	0.455 *Kg/kWh*	8 *hours*	16.293	3.568
Staff	Human mobility	6	0.08 *m^3/h*	1.964 *Kg/m^3*	9 *hours*	8.484	1.858
PC	Power Consumption	6	60 *W*	0.455 *Kg/kWh*	8 *hours*	1.310	0.287
Printer	Power Consumption	3	110 *W*	0.455 *Kg/kWh*	6 *hours*	0.901	0.197
Subtotal	-	-	-	-	-	34.605	7.579

[*Table 5-13: Carbon emissions of Packaging*]

f) Goods Output

Element	Emission Mode	Quantity (A)	Activity Data (B)	Emission Factor (C)	Energy Consumption (D)	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)
Dock	-	6	-	-	-	-	-
Truck	Fuel Consumption	6	23.52 *L/100km*	2.689 *Kg/L*	1 *km*	3.795	0.831
Forklift	Power Consumption	6	6.4 kW	0.455 *Kg/kWh*	5 *hours*	87.360	19.132
Staff	Human mobility	12	0.08 m^3/h	1.964 Kg/m^3	9 *hours*	16.969	3.716
PC	Power Consumption	12	60 *W*	0.455 *Kg/kWh*	8 *hours*	2.621	0.574
Printer	Power Consumption	3	110 *W*	0.455 *Kg/kWh*	6 *hours*	0.901	0.197
Subtotal	-	-	-	-	-	111.645	24.450

[*Table 5-14: Carbon emissions of Goods Output*]

Step 5: Calculation of elements that considered in overall

Element	Emission Mode	Quantity (A)	Activity Data (B)	Emission Factor (C)	Energy Consumption (D)	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)
Biulding	-	10,500 m^2	-	-	-	-	-
Throughput In.	-	4,500 *t/y*	-	-	-	-	-
Throughput Out.	-	4,500 *t/y*	-	-	-	-	-
Air condition	Power Consumption	1	336 *kW*	0.455 *Kg/kWh*	1219 *Hours(year)*	850.962*	186.361
Lights	Power Consumption	450	60 *W*	0.455 *Kg/kWh*	9 *hours*	110.565	24.214
		50	60 *W*	0.455 *Kg/kWh*	1219 *hours*	-	7.174
Office	-	100 m^2	-	-	-		
Staff	Human mobility	15	0.08 m^3/h	1.964 Kg/m^3	9 *hours*	21.211	4.645
PC	Power Consumption	15	60 *W*	0.455 *Kg/kWh*	8 *hours*	3.276	0.717
Printer	Power Consumption	2	110 *W*	0.455 *Kg/kWh*	6 *hours*	0.601	0.132
Commuting	Fuel Consumption	55	5.8 *L/100km*	2.274 *Kg/L*	44 *km*	319.179	69.900
Subtotal	-	-	-	-	-	1338.554	293.143

[*Table 5-15: Carbon emissions of Other Elements*]

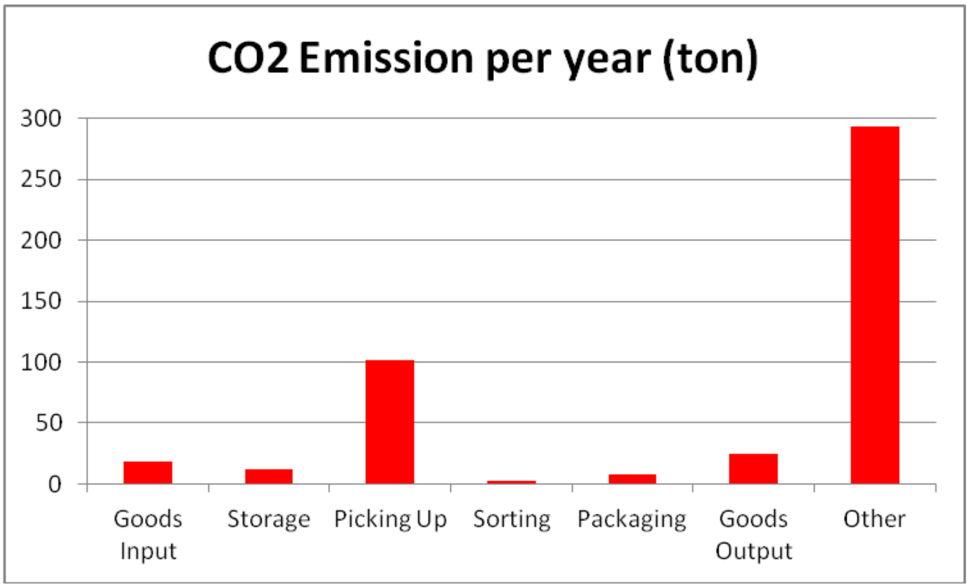
* Average 5.566 hours per working day.

Step 6: Calculation of system

a) Accumulated by subsystems

Subsystem	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)	Note
Goods Input	84.691	18.547	
Storage	56.824	12.444	
Picking Up	462.047	101.188	
Sorting	9.872	2.162	
Packaging	34.605	7.579	
Goods Output	111.645	24.450	
Other	1338.554	293.143	
Total	2098.238	459.513	

[*Table 5-16: Total Carbon emissions by subsystem*]

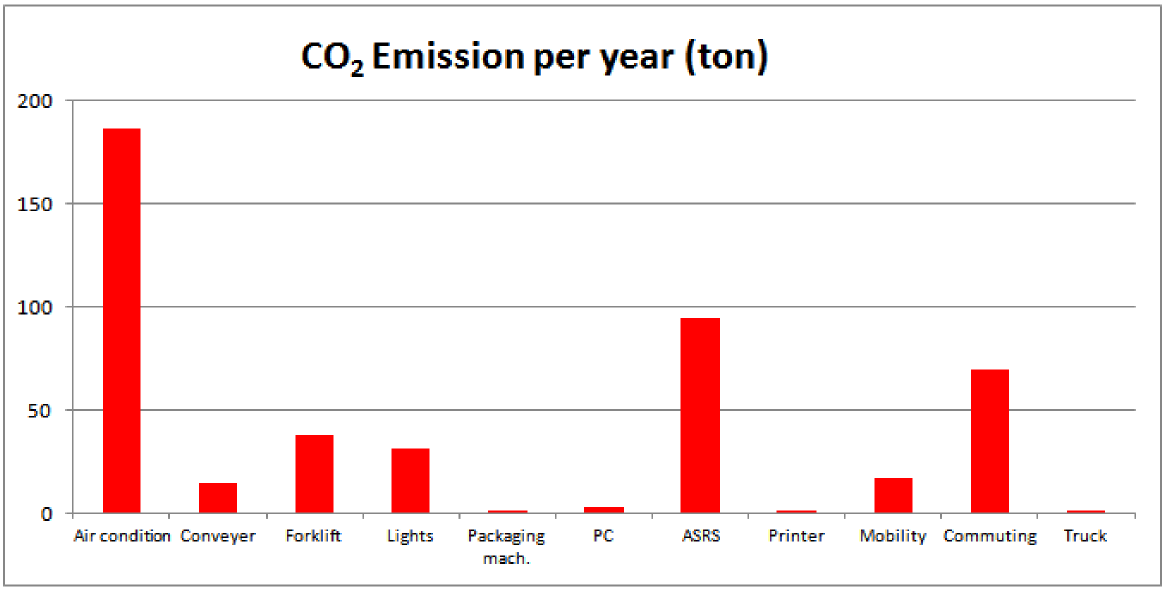


[*Fig 5-16: Distribution figure by subsystem*]

b) Accumulated by the subsystem

Element	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)	Note
Air condition	850.962	186.361	
Conveyer	67.886	14.867	
Forklift	174.72	38.264	
Lights	143.325	31.388	
Packaging mach.	7.617	1.668	
PC	12.012	2.631	
ASRS	432.432	94.703	
Printer	6.006	1.315	
Staff	77.774	17.033	mobility
	319.179	69.900	commuting
Truck	6.325	1.385	
Total	2098.238	459.513	

[*Table 5-17: Total Carbon emissions by element*]



[*Fig 5-17: Distribution figure by element*]

5.4. Conclusion

After getting relevant parameters, calculation is not complex. The result of calculation is a series of data, and only gives an intuition for judgment. In order to further improvement of carbon emissions, it is important to analyze, study and evaluate the result of calculation.

5.4.1. Evaluation

5.4.1.1. Other carbon emissions sources

There are many carbon emissions sources in a real distribution center and didn't be included in this topic. For analysis of a detailed and real (not an abstract system) distribution center, some carbon emissions sources must be considered, such as business travel, commuting of staffs, etc. These carbon emissions sources were important, because they emitted a large number of carbon dioxide (and other greenhouse gases) in fact. But for an abstract distribution center system, according to the definition of distribution center system, these carbon emissions sources didn't be discussed and calculated in this topic.

a) Business travel
   As almost necessary business activities for any organizations, business travel is a very important carbon emissions sources. The ways of business travel may be were by train, by plane, by ship, etc. Different ways contributed their own carbon emissions.
   Carbon emissions of business travel were huge. In the example mentioned in chapter 5 (PNNL 2007 CO_2 emissions), the percentages of business travel up to 40% of total carbon emissions.

In this topic, we defined activities only within a distribution center, rather than all activities related to distribution center. Business travel was outside the scope of defined distribution center system, so it was not be mentioned and calculated any more.

b) Waste
Waste includes waste water, waste gas, waste paper, garbage, and so on. For a distribution center, waste was not so much. In our model of distribution center system, waste gas was not exist, waste water and garbage were extremely few, because there was only one shift and 8 hours working time.
Most of the papers were packaging boxes and labels. They were purchased from suppliers, and sent to the customer with goods together. Only damaged packaging boxes and labels would be treated as waste, therefore, the quantity of waste paper was extremely limited. In this topic, waste was also not be mentioned and calculated.

c) Transportation
The amount of carbon dioxide generated by transportation is great. No matter a distribution center has a fleet or not, the carbon emissions produced by transportation must be considered. According to the defined boundaries of the system, the transportation was defined as movement of vehicle within the precincts of distribution center instead of entire transportation process. in this topic, although the moving distance was short, the carbon emissions was still considered and calculated.

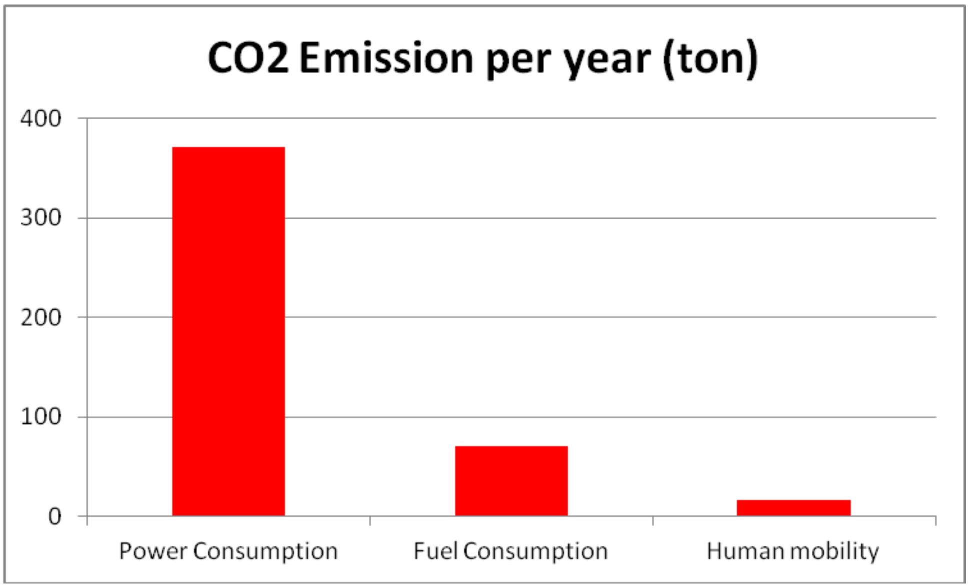
5.4.1.2. Evaluation

Relative to other organizations, especially production-oriented enterprises, carbon emissions of a distribution center were not high. The main reason was that only a large number of electric power consumed and no additional carbon dioxide produced during operation process of distribution center. In this topic, transportation was defined as in a short distance, so fuel consumption was in a very low level.

a) CO_2 Emissions by emission mode

Emission Mode	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)	Percentage (per year)
Power Consumption	1694.960	371.195	80.78%
Fuel Consumption	325.504	71.285	15.51%
Human mobility	77.774	17.033	3.71%
Total	2098.238	459.513	100.00%

[*Table 5-18: CO_2 Emissions by emissions mode*]



[*Fig 5-18: Distribution of CO_2 Emissions per year by emission mode*]

Power consumption is the biggest emission source for a distribution center, because a modern distribution center uses usually a large number of electrical equipment, includes electric powered forklift. Normally, electric powered transportation tools emit less carbon dioxide (greenhouse gases) than fuel powered tools.
Electricity is considered as "clean" energy because it doesn't emit carbon dioxide (greenhouse gases) when using. Carbon emissions of electricity we calculated is based on the carbon emissions during electricity generation. As we know, there many technologies for electricity generation, such as Thermal power (coal, oil, natural gas), nuclear power, hydropower, wind power, etc. With the development and use of low-carbon electricity generation technologies (Biomass, PV, Marine, Hydro, Wind, Nuclear), carbon emissions of power consumption will be further reduced.

Fuel consumption is also a main source of carbon emissions. Though human tries best to improve the quality of fuel in order to reduce carbon emissions, air pollution caused by burning of fuel is still a serious problem nowadays. In this topic, carbon emissions (produced by fuel consumption) were mainly produced by commuting. Transportation was limited to a specific area (within the precincts of distribution center), and carbon emissions produced by transportation were very low. If we considered entire transportation process, carbon emissions of fuel consumption would be increased sharply.

Carbon emissions produced by human breathing (mobility) are also cannot be ignored, even though it is really lower than other carbon emissions. Breathing is basic and necessary activity to human being.

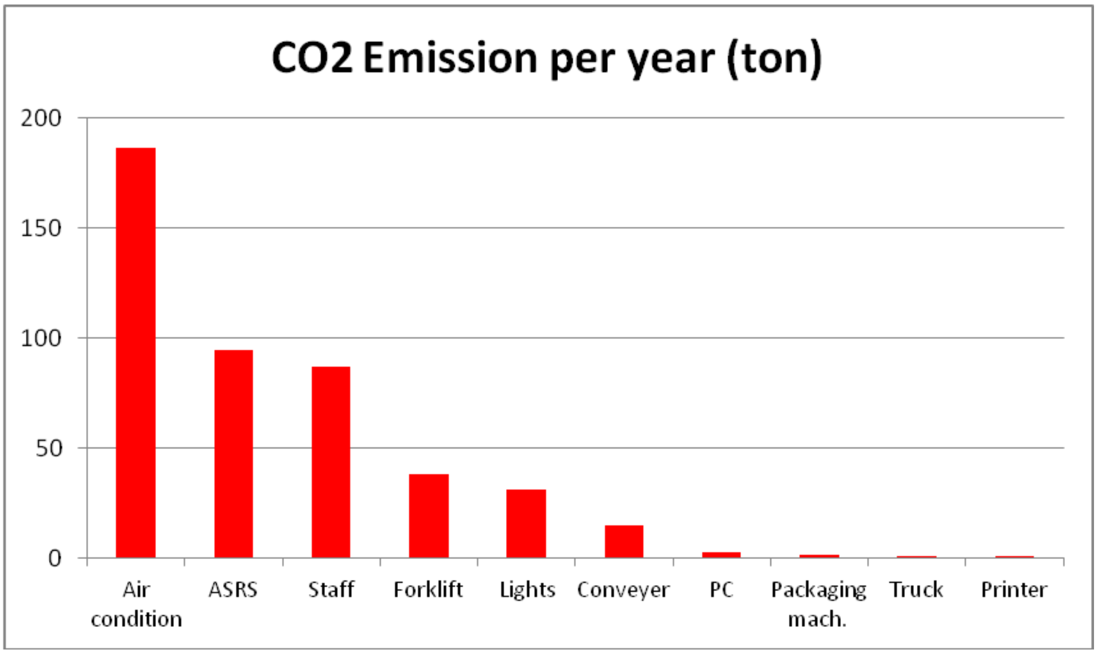
For those non-production-oriented enterprises, the proportion of carbon emissions produced by breathing is relative larger than others.
In many cases (e.g. the example mentioned in chapter 5), carbon emissions produced by breathing were not calculated, but in this topic, the data showed that it was also an important emission source.

b) CO_2 Emissions by element

Element	CO_2 Emissions per day (kg)	CO_2 Emissions per year (ton)	Percentage (per year)
Air condition	850.962	186.361	40.56%
ASRS	432.432	94.703	20.61%
Staff *	396.953	86.933	18.92%
Forklift	174.72	38.264	8.33%
Lights	143.325	31.388	6.83%
Conveyer	67.886	14.867	3.24%
PC	12.012	2.631	0.57%
Packaging mach.	7.617	1.668	0.36%
Truck	6.325	1.385	0.30%
Printer	6.006	1.315	0.29%
Total	2098.238	459.513	

* The element "Staff" includes two parts, i.e. human mobility and commuting, because these two behaviors both belong to activities of staff.

[*Table 5-19: CO_2 Emissions by Element*]



[*Fig 5-19: Distribution of CO_2 Emission per year by Element*]

Carbon emissions produced by air condition is the biggest. In the research report [89] written by G.N. Dunn, I.P. Knight and E.R. Hitchin, authors given the relationship between annual energy consumption and power of air condition system. In the model of distribution center, assumption of running time of a central air conditioning was about 1219 hours per year. That means the air condition was not kept in working whole year. At the same time, we didn't consider heater because heating was a main function of a central air conditioning. Except 10 percent of lights, other elements (equipment, devices, staffs …) were considered as only working one shift per day.

ASRS contributed second biggest quantity of carbon emissions because of its high power. The reason of high carbon emissions produced by staff was fuel consumption in commuting.

Low carbon emissions of printers, packaging machines and PCs were contributed by their low power.

5.4.2. Development

Carbon footprint is a dynamic result. Reducing carbon emissions (greenhouse gases emissions) is also continuous development issue. In order to get accurate results of carbon emissions for reference, experts developed a series of guidelines, standards and calculation tools to support studying of carbon emissions. For a detailed studying (e.g. distribution center mentioned in this topic), there are many aspects should be developed in future.

a) Consideration of potential emission sources
Except carbon emissions sources calculated and mentioned before, there are still other some carbon emissions sources, for example, carbon emissions of buildings.

Usually, building itself doesn't produce carbon dioxide. But during building construction, operation and maintenance, it would consume a large number of building materials and generate enormous quantities of waste. A data from United Nations Environment Programme (UNEP) shows that account for 30% of global carbon emissions. At the same time, concepts of low carbon building and zero-energy building were accepted by human. These two concepts mainly focus on reducing carbon emissions of building itself with new technologies. For a distribution center system we studied in this topic, emphasis is operation of distribution center, so we didn't consider the carbon emissions of building.

Additionally, external person (e.g. suppliers, customers…), external vehicles and external equipment (for maintenance, testing, and so on) are also emission sources, and didn't be mentioned in this topic.

b) Universality of distribution center
We constructed a relative typical distribution center system in order to analyze carbon footprint of a common distribution center. For this

purpose, we abandoned some non-universality elements, such as cold storage in food industry, anti-static equipment in electronics industry, and anti-leak/anti-explosive equipment in chemical industry, etc. For a specific distribution center, these elements must be considered and calculated because they would emit a large number carbon dioxide, but in this topic, these elements were not been mentioned.

As a universal result, the values achieved in chapter 5 were not accurate for specific distribution center. These values should be made some revises according the specific distribution center when using.

c) Expand of distribution center system
In this topic, the boundaries of distribution center system were been limited to a relatively small range, i.e. within the precincts of distribution center. Some activities were not been considered and calculated, such as transportation, business travel, commuting, and so on.

As we know, distribution center is a node in business/logistical chain. In this topic, we considered activities only within node, and its carbon emissions showed not much compare to other organizations. If we expand the boundaries and contain activities mentioned above, the result of carbon emissions will be significantly increased. It should be noted that for those distribution centers in different industries and different regions, differences of transportation, business travel and commuting are huge.

d) Improve data collection
We applied some data from investigation and studying to construct a distribution center model. These investigations and studying had their limitation, for example, they couldn't investigate all types' distribution centers, or all distribution centers in a specific industry. On the other hand, relevant emission parameters were not accurate because some of them had to be assumed rather than achieved directly with analysis or calculation. An obvious example was emission factor of electric power – only compositions of electricity power (the proportion of various types' electricity generating capacity) were known, the emission factor was accurate.

In order to get more accurate result, it is necessary to investigate more distribution centers and relevant parameters. Based on investigation, more detailed and accurate analysis and calculation are possible.

e) Improve calculation approach
In this topic, we applied SysML to build approach of calculation. Exactly, whatever approaches of calculation, the most basic principles of them are similar, i.e. carbon emissions are associated with energy consumption modes and are proportional with energy consumption. In

order to get more accurate and universality result, improvement of calculation approach is possible. For example, integrating other approaches (PAS2050, GHG protocol), selecting more appropriate emission factors, and so on.

f) Seeking for opportunities of reducing carbon emissions
Reduction of energy consumption is the main method of reducing carbon emissions. In a distribution center system we constructed, the most possible opportunity is reduction of electricity power consumption. For a distribution center, following actions will helpful for reducing carbon emissions:
- Improving equipment utilization
- Improving staff efficiency
- Using renewable energy sources (e.g. solar)
- Using environmental technologies
- And so on.

g) Cooperation with relevant partners
It is possible to reduce carbon emissions through cooperation with relevant partners, though some emissions are outside of distribution center system defined before. For example, cooperation with suppliers to arrange appropriate transportation time and route. Another example is cooperation with investors to invest new environmental technology.

6. Summary

The concept of carbon footprint has been well known in the past few decades. The concern of carbon footprint has also became more and more high along with increasing severity of global warming issues. At the same time, calculating carbon emissions of associated individuals and organizations and seeking opportunities to reduce carbon emissions became global trends. As a node of business chain / logistical chain, distribution center is an important process. Calculation of carbon footprint of distribution center and reduction of carbon emissions are very important actions.

In this topic, at first we explored the development and importance of carbon footprint, introduced some important definitions like carbon footprint, discussed attributes, delimitation, requirements and basic approaches, and given goals of this topic – construction of model and calculation of carbon footprint.

In chapter 2, according to the requirements mentioned in chapter 1 (brief introduction), we collected the relevant laws, regulations and requirements in different levels (global, regions, nations) in order to know/understand requirements of carbon emissions. Of course we introduced mechanism and hazards of carbon emissions.

In the following chapter, we analyzed the structure of distribution center system, defined boundaries of system, divided processes, and discussed components in the system. As a requirement of important input of modeling, we analyzed relevant functions of every processes and components.

Based on the analysis in chapter 3, we constructed a model of distribution center using top down approach (V-model) in chapter 4: defined scale of distribution center, assumed some important characteristics, analyzed every subsystems, elements and their relationships, etc. Finally, we got an entire model of distribution center system with important data and parameters. This was the basis of calculation.

In chapter 5, we referenced relevant calculation approaches and examples, introduced the approach of SysML, determined the relevant parameters (especially assumption of energy consumption), calculated carbon emissions of the model of the distribution center, and got final calculation results.

The goal - construction of model was completed in chapter 4, the goal - calculation of carbon footprint was achieved in chapter 5.

Carbon emissions of distribution center had limitation because of definition and boundaries of the model. The model itself was abstract of specific objects, and had universal significance. Therefore, the results of calculation also had universal significance. In different industries and regions, the size and facilities of distribution centers had huge difference. These differences didn't be shown in the results of calculations. For specific examples, the results are different according to different distribution centers.

For the distribution center with universal significance, the results of calculation showed that the power consumption was a major source of carbon emissions, and air condition was the major source of power consumption. On the other hand, carbon emissions produced by fuel consumption will rise sharply, when the system boundaries expanded to include transportation and business traveling (which can be seen from the example in 5.1.2).

In the distribution center system that defined in this topic, reduction of power consumption is the greatest opportunity to reduce carbon emissions. If more environmental technologies (e.g. renewable energy sources) can be applied , carbon emissions will be effective reduced.

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