PUBLIC HEALTH IMPACT ASSESSMENT IN A SUPPLY CHAIN NETWORK DESIGN PROBLEM

BY

THI TRUONG NGUYEN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF MASTER OF
ENGINEERING (LOGISTICS AND SUPPLY CHAIN SYSTEMS
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SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
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A Thesis Presented

By
THI TRUONG NGUYEN

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Abstract

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Minimizing environmental impacts due to logistics activities has long been recognized as part of a way to promote sustainable supply chain. Facility location decisions play a critical role in the strategic design of supply chain and hence have a long-term impact on its cost and environmental performance. In this study, Operations Research and life-cycle impact assessment techniques are used to estimate the burden on local population's health caused by facility location decisions. Specifically, our primary goal is to minimize the impacts on local population's health and Disability Adjusted Life Years (DALYs) is used as a metric to quantify that impacts. A mixed integer linear programming model is developed based on a case study located in Can Tho city, Vietnam. Geographic information system (GIS) mapping software is used to estimate the number of people affected by the transportation. The results of the study show that population density along different parts of transportation routes is the main factor influencing the selection of optimal solutions.

Keywords: Network design, Environment, Health impact, Optimization, DALY

Table of Contents

List of Figures

Figures **Page**

List of Tables

Tables **Page**

Chapter 1
Introduction

1.1 General

Cost minimization or profit maximization has long been recognized as one of the primary objectives for a supply chain network design optimization problem. During the past years, the environmental performance has gained much consideration by researchers and practitioners, due to the growing concerns of environment and sustainability. Organizations are aware of the importance of a clear understanding of the environmental impacts of their supply chain activities. Mitigation measures and strategies of transport-related pollution emissions are an ongoing effort required for sustainability development. At an international level, with the presence of regulations and standards such as the Kyoto protocol and the ISO14000, organizations are obliged to set their pollution emission targets and mitigation plans. This leads to the growth in practices and research efforts on how to integrate the environmental dimension into the strategic design of a supply chain network, with an aim to reduce and control the long-term environmental impacts of activities within a supply chain.

Greenhouse gas (GHG) emissions is a widely used environmental impact indicator for range of activities including transport. The use of GHG indicator helps increase public understanding about the degree of the potentially occurred global warming and climate change impacts. For instance, it is well known that transportation is one of the main contributors to GHG emissions, given that transport-related CO_2 emission accounts for as much as 23% of the global emissions in 2012 (IEA, 2014). At any rate, it must be noted that global warming is only part of the overall environmental impact caused by transport activities. The previous study reports that long-term exposure to air pollutants, such as particulate matter (PM), oxides of nitrogen, ozone, carbon monoxide, and benzene, can increase the risk of a number of important health problems related to respiratory and cardiovascular diseases, cancer, and adverse reproductive outcomes (Bates, 1992). Obviously, there is a need for a more comprehensive environmental impact indicator, which allows us to capture all the major potential environmental impacts of our activities.

Environmental impact can be classified in terms of impact scales: global, regional, and local impacts. At the same time, the impact can be divided into three impact areas: human, ecosystem, and natural resource, according to LCIA methodologies (Goedkoop et al., 2009). Impact on human health is one of the areas with insufficient research attention, especially when considering recent health impact statistics. The number of premature deaths worldwide due to air pollution increased from 1.3 in 2008 to 3.7 million deaths per year in 2012 (WHO, 2012). Despite this fact, the assessment of public health impact remains a research gap in the supply chain modeling literature, as described in the following parts of this paper.

In this thesis, the strategic planning of facility location is our main focus. The problem is commonly referred to as supply chain network design (SCND). Dekker et al., 2012 conclude that the impacts on the environment can be strongly influenced by logistics decisions, including the selection of facility location, supplier and transportation mode. Among them, facility location decision is the primary determinant of transport emissions. In light of this conclusion, this thesis intends to develop a SCND model that capable of handling both cost and public health impact as the objective functions. The ultimate goal is to develop a tool that can be used to design a supply chain network with a good balance between cost and health burden on local population.

In a nutshell, this thesis focuses on the development of a methodology for public health impact assessment in a SCND problem. The main scholarly contribution lies in the use of geographic information system (GIS) software and DALY concept to assess the number of affected population and their health burden under different network designs. A supply chain network model developed in this thesis can be used by urban planners to gain insight into the economic and public health performances of their network design. A case study of supply chain network in Can Tho city, Vietnam, is used in this thesis to illustrate the methodologies and assessment procedures. The details of the problem, research objectives, scope of study, and scholarly contribution are described in the following parts of the chapter.

1.2 Statement of problem

In this thesis, a case study is carried out using the data of Can Tho city in Vietnam. According to the development plan of Can Tho, the city has a goal to become a modern industrial city in the near future, with the annual industrial growth rate of 16.7% in the period of 2016-2020 (Can Tho Goverment, 2005). Due to the nature of air pollution issues in fast growing cities, the government is fully aware the city's environmental protection plan will not keep pace with the growing air pollution problems. Among all industrial activities, transportation is the main contributors to GHG emissions to the atmosphere. In this regard, the government has encouraged a move to lower carbon emissions and air pollutions by improving the environmental efficiency of transport-related activities. There are various mitigation measures to reduce the released amount of CO_2. For example, one of the efforts is to promote the use of vehicles fueled by low-carbon energy sources such as natural gas and liquefied gas (Can Tho Goverment, 2005).

To tackle air pollution and adequately protect public health, the ability to monitor and control the emissions of pollution from transportation is important. Thus far, CO_2 emissions are mainly used as the environmental impact indicator. The use of such indicator is necessary to mitigate and control the released amount of GHG, but not sufficient when dealing with air pollution problems. Aside from global warming and climate change, transportation is the source of many hazardous gases and pollutants such as NOx, SOx, and PM emissions. There is a need to look at all the pollutants with the use of a more comprehensive environmental impact indicator in order to mitigate the air pollution in Can Tho city.

Human health assessment in SCND has also emerged as an importance area of investigation in terms of research. It is worth mentioning here that two main research gaps identified in this thesis are related to 1) the assessment of public health impact across specific geographical areas and 2) the use of human health damage as an environmental impact indicator and optimizing parameter in a SCND problem. Firstly, most previous health impact studies only focus on reducing the released amount of pollutants, not the damage or actual burden on people living in exposed areas. Secondly, the use of damage to human health indicator in transportation and network problems is very limited. Damage indicators, used in previous transportation and network studied, are usually limited to endpoint single score indicators, such as Eco-point and Eco-indicator. The score does not provide a meaningful measure of human health impact. This thesis provides a summary of the evolution of green SCND research works and discusses the research gaps in more detail in the chapter of literature review.

1.3 Purpose of the study

In response to the mentioned problems, this thesis aims to develop a new approach to quantify and minimize public health impact of a supply chain network on local population. A bi-objective MILP optimization model is formulated to search for a set of optimal compromise solutions between total cost and public health impact objectives. The assessment of public health impact is carried out based on DALY concept, with the health impact expressed as the sum of years of life lost due to premature mortality and disability in population. A three-echelon supply chain case study is used to demonstrate how to estimate public health impact. GIS software is used to estimate the number of population affected by transport emissions.

1.4 Scope of the study

This SCND study involves the formulation of bi-objective mathematical optimization models. The two objectives under consideration are transportation cost and public health impact. Public health impact caused by transportation activities are assessed using LCA (Life cycle assessment) methodology. The assessment provides a valuable insight into the health damage to local population, caused by transport pollution. The potential damage is calculated based on human health damage category of an endpoint LCIA method. The primary factor determining the degree of the damage is the population density of areas affected by transport pollution. Other factors under consideration are traveling distance and the carrying weight of vehicles. In the calculation, the damage due to local-scaled impact categories including toxicity, photochemical oxidant formulation, and PM are accounted for, whereas the global-scale impact categories including climate change and ozone depletion are excluded. This is to visualize the impact of transportation activities between suppliers and a manufacturer in a supply chain network on local population. The damage results are presented in terms of public health impact, which is the overall health damage on population residing along transportation routes. The estimation of the number of affected population in this study is made via the use of GIS software.

The proposed optimization model is applied to an inbound supply chain in Can Tho city, Vietnam. The case study encompasses the flow of a single product from suppliers to a manufacturer. The public health impact represents the total health burden for Can Tho city. It must be noted that the calculated damage is based on DALY coefficients obtained from Thai National LCI database. Both Thailand and Vietnam are located in Southeast Asia. It is assumed that the use of Thai database for the impact assessment in Vietnam is reasonable.

1.5 Significance of study

To the best of our knowledge, it is the first time that the concept of DALY, a metric promoted by WHO to be used as a measure of the global burden of disease, is used in conjunction with GIS software to assess the overall damage to human health across geographic areas, affected by the operation of a supply chain network.

The case study used in this work, Can Tho city, is one of the cities in Vietnam, which undergoes a dramatic urban transformation and air pollution problems during the past decade. The results of this work will enable decision makers to gain insight into useful information for SCND, which includes 1) the spatial distribution of the public health impact caused by transportation activities in a supply chain network and 2) the effect of demographic data (population density) on the public health impact and optimal supply chain network configuration.

Chapter 2
Literature Review

2.1 Green logistics

The use of green logistics for a better equilibrium between economic and environmental objectives, has received much interest in recent years. Green logistics concept is widely implemented and included in the design of supply chain networks by various leading companies, such as IKEA, IBM, and HP, to improve their corporate environmental reputation and competitive advantage. Haw-Jan & Steven, 1995 define green logistics as *"an environmentally responsible logistics system"*. It starts from raw material acquisition, production, packaging, transportation, warehousing to end-users' hands and also includes waste recycling and disposal. The scholar of Rodrigue et al., 2013 states that green logistics is *"Supply chain management (SCM) practices and strategies that reduce the environmental and energy footprint of freight distribution. It focuses on material handling, waste management, packaging, and transport".* As compared to traditional logistics, where economic benefits are obtained at the cost of ecological damage, the concept of green logistics provides a valuable insight into environmental impacts caused by logistics activities, with an aim to mitigate amount of energy consumption, resource consumption, and pollutant emissions.

It is rather difficult to determine when green logistics concept began to gain research attention. It is recognized that many people start to concern about environmental problems caused by logistics activities since the early 1980s, as described by Quan et al., 2008. Wardrobe (1981) and Whitelegg (1988) analyzes the negative impacts of exhaust emissions from vehicles. According to IVECO-Ford (1990), vehicles produce 16% of CO_2 emissions that can be attributed to road transport (Cooper, 1995). Their study is conducted to understand the effect of carbon emissions reduction scheme in all aspects of logistics processes, such as purchase, storage, processing, package, and waste recycle (De-ling & Rong, 2011). After that, the focus on CO_2 emissions indicators can be found in various green logistics studies.

For example, Rai et al., 2011 provide a valuable insight into low carbon strategy through the optimal design of a distribution warehouse. Li et al., 2012 analyze and minimize the overall carbon emissions due to over-packaging and low recovery rate. Hsu et al., 2013 evaluate and select appropriate suppliers of electronic products based on carbon criteria.

These previous research efforts identify transportation as one of the main contributors to global GHG emissions due to the use of fossil fuels. Transport emissions can be greatly affected by logistics decision making, which can be classified into three categories including operational, tactical, and strategic levels. In particular, at the strategic level, any decision making tends to have a much more significant and long-lasting impact on the environment and well-being of people, residing within the supply chain network. Decision making usually involves the determination of locations, numbers, and capacities of the network facilities and the flow of materials between them. The resulting optimization problem, considering these parameters, is generally referred to as facility location problems or SCND problems. In the area of green SCND, which is the research focus of this thesis, the objective is to simultaneously minimize cost and environmental impacts caused by logistics activities. The incorporation of environmental dimension into a SCND problem requires researchers to set up a multi-objective optimization model to investigate the tradeoffs between the economic and environmental objectives, as shown in Table 2.1. Some of the related studies are reviewed here in order to identify the research gap that this thesis intends to fill.

Table 2.1 Previous green SCND studies.

Author	**Model formulation**	**Economic objectives**	**Environment objectives**	**Other objectives**	**Multi period**	**Multi product**	**Solving method**
Hugo et al., 2005	MILP	✓	✓	-	✓	-	U
Frota Neto et al., 2008	U	✓	✓	-	-	-	U
Harris et al., 2009	U	✓	✓	Uncovered demand	-	-	NGSA-II algorithm
Zamboni et al., 2009	U	✓	✓	-	-	-	U
Giarola et al., 2011	MILP	✓	✓	-	✓	✓	U
Wang et al., 2011	MINLP	✓	✓	-	-	✓	Normalized normal constraint
Kostin et al., 2012	MILP	✓	✓	-	-	-	ε constraint method
You et al., 2012	MILP	✓	✓	Number of jobs	-	-	ε constraint method
Xifeng et al., 2013	MILP	✓	✓	Service level	-	-	ε constraint method Greedy heuristic
Bing et al., 2014	MILP	✓	✓	-	-	✓	U
Molina et al., 2014	MO	✓	✓	-	-	-	Tchebycheff method
Nurjammi et al., 2014	MILP	✓	✓	-	-	-	Weighed sum method Tchebycheff method
Soysal et al., 2014	MOLP	✓	✓	-	-	-	ε constraint method
Yue et al., 2014	MILP	✓	✓	Number of jobs	-	-	ε constraint method
Accorsi et al., 2015	MILP	✓	✓	-	-	✓	U

Colicchia et al., 2015	MILP	✓	✓	-	-	-	Weighted sum method
De-León Almaraz et al., 2015	MILP	✓	✓	Inherent index	✓	-	ε constraint method

Notes:

U: Undefined

For most studies, the released amount of GHG is commonly used as the environmental performance indicator in the multi-objective models. Hugo et al., 2005 formulate a bi-objective MILP model to enable the strategic design and planning of hydrogen supply chain. The proposed model can capture the possible relationships between various components of hydrogen supply chains. GHG emissions from delivering hydrogen to a customer is accessed using an LCA methodology. The evaluation of economic and environmental performance of a strategic design of renewable energy supply chain are found in subsequent works. For example, Zamboni et al., 2009 take into account environmental impacts caused by various transportation modes in the supply and distribution channels of biomass. In their study, the impacts are quantified in terms of global warming indicator (GWP). You & Wang, 2011 propose a model for a biomass-to-liquid supply chain. The more comprehensive consideration of environmental impacts from facility locations, production technologies, capacity assignments, and transportation is presented. Giarola et al., 2011 develop a framework for a multi-period supply chain network of hybrid bioethanol. Their proposed model provides decision makers a quantitative analysis of economic and environmental performance of different supply chain configuration. Besides the supply chain of renewable energy, the focus on economic and GHG emissions minimization objectives can be found in supply chains of various industries. For instance, Bing et al., 2014 propose a mathematical model for a plastic supply chain with multi-product. The environmental impacts of the supply chain are considered through GHG emissions from transportation activities. Soysal et al., 2014 suggest a multi-period logistics network for a beef exporter whose transportation activities are outsourced to a logistics firm. The amount of GHG emissions of different modal transportation is measured in their study. Accorsi et al., 2015 propose a model for a close-loop supply chain network of furniture. In their study, the environmental impacts are measured based on the overall GHG emissions from facilities and transportation activities at the end-of-life and other life-cycle phases.

Until recently, previous green SCND studies start to consider additional supply chain capabilities including responsiveness (Zhang et al., 2014), resilience (Cardoso et al., 2015), job opportunities (You et al., 2012), and risk management (Olson & Swenseth, 2014). This introduces a higher degree of complexity into the existing multi-objective SCND problems. For example, Xifeng et al., 2013 introduce a multi-objective model considering cost, environmental impacts, and customer service. De-León Almaraz et al., 2015 present a multi-objective model for a five-echelon hydrogen supply chain. The proposed model takes into account cost aspects, global warming impact, and the risk associated with manufacturers, storage facilities, and transportation units. Yue et al., 2014 formulate a model considering economic, environmental, and social impacts for a bioelectricity supply chain.

2.2 Public health impact

Besides global warming impact, the human health due to the exposure of transport emissions containing hazardous gases and PM cannot be overlooked, especially for populated areas (Schwela, 2000). Long-term exposure to air pollutants such as PM, oxides of nitrogen, ozone, carbon monoxide, and benzene, can increase the risk of a number of important health problems, related to respiratory and cardiovascular diseases, cancer, and adverse reproductive outcomes (Bates, 1992). Despite the known adverse effects of transport emissions, there are very few studies aimed to mitigate the health impact due to transport emissions through the development of SCND model. Chang & Lin, 2013; Mallidis et al., 2012 demonstrate how to reduce the air pollutant release in a multi-objective SCND problem. Specifically, Mallidis et al., 2012 formulate a MILP model that can minimize cost and environmental impacts caused by different transportation modes and facility locations. These impacts are measured by the total amount of CO_2, CO, PM, SO_2, and NO_X emissions from the operations occurring in this supply chain. Following this interest, Chang & Lin, 2013 aim to reduce environmental impacts along the supply chain network of solid waste. The pollutant emissions from this network, including SO_x, NO_x, CO, and PM, are estimated and are later accounted for in a MILP model.

The consideration of human health impact in these previous studies is based on the amount of air pollution released, not the exposure amount. The need to look into exposure impact and damage oriented-impact is highlighted by several recent studies. Bojarski et al., 2009 and Kostin et al., 2012 take into account economic and four damage indicators from Eco-indicator 99 (EI-99), including human health, ecosystem, resources, and climate change. Their model is formulated as a MILP model, allowing the observation of the possible tradeoffs between damage categories and economic performance. Mele et al., 2011 develop a model that can maximize profit and minimize environmental impacts for the design of sugar cane supply chain. The environmental impacts are quantified in terms of global warming and 11 impact indicators, which are later translated into a single-score damage indicator.

To this end, the use of aggregated LCA-based indicators is useful in bringing various potentially occurred impacts into SCND consideration. It helps decision makers to envision a comprehensive view of the potential environmental impact. Environmental burdens and adverse impacts on human health, associated with operations and transportation activities within a supply chain, can be better accounted for, as compared to when the emission of greenhouse gases or any transport pollution is solely used as an environmental performance indicator. At any rate, the models and methodologies, proposed by these previous studies, do not provide an assessment of potential population exposures, which is one of the essential procedures used to quantify the impact of air pollution on public health, according to WHO (Krzyzanowski et al., 2002).

In order to fill the above gaps, this thesis provides an impact assessment methodology focusing on human health caused by transportation activities of SCND. The overall health damage across geographical areas is measured and defined as the public health impact. A geographical software is used in estimating the number of affected population and the public health impact. It is shown that the dynamics of city areas and demographical data are needed to be analyzed in public health impact assessment. It is also the first time that public health impact is assigned as one of the objectives in a SCND problem. The detail of approaches and methodologies, used in this research, are elaborated in the next chapter.

Chapter 3
Method of Approach

3.1 Population estimate

In this thesis, the analysis of geographic data, including street and city layout, administrative boundary, and demographic data, allows us to evaluate the impact of urban dynamics on the environmental burden carried by the city. In particular, our focus is to investigate the health impact of transport emissions from truck fleets on people living in different geographical areas across Can Tho city. The impact is later assigned as one of the optimizing objectives in our MILP model. To investigate such impact, there is a need to estimate the number of affected population. In this thesis, a GIS software called ArcGIS is used in population estimate.

ArcGIS (Version 10.2), developed by the Environmental systems research institute (ESRI), is a software tool that can be used to solve SCM problems. The software allows decision makers to analyze geographic data including street and city layout, administrative boundary, and demographic data. A Geo-database and an electronic map can be generated, allowing the optimization of various supply chain parameters in SCM problems, such as vehicle routing and facility location problems (Cheng & Phillips, 2011), to be realized.

In this thesis, the number of people affected by these emissions, along different road segments, is estimated based on population density data and the size of affected areas. Firstly, the size of affected areas around road segments is estimated by using ArcGIS software. The area within 5,000 m of each road segment is defined as the affected area. People living in this area is assumed to be affected by transport pollution. This distance is used by the previous studies to estimate the number of people exposed to PM emissions (Gouge et al., 2013; Greco et al., 2007). In this study, the affected area along each transportation segment is located by ArcGIS software as shown in Fig. 3.1.

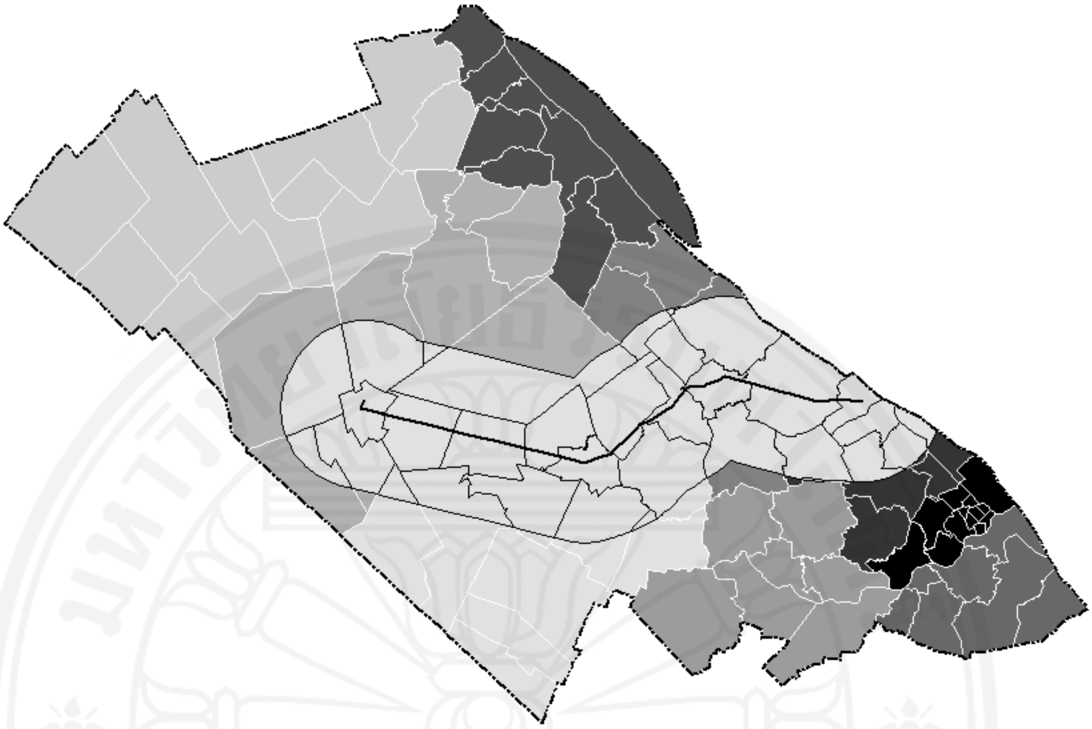

Figure 3.1 The approximate boundary of affected areas along a transportation segment.

Secondly, the population density is assumed to be uniformly distributed within each sub-district. The size of each affected area is multiplied by its population density to estimate the number of affected population. In this study, the population density data of each sub district is obtained from (Minh Nguyen, 2012).

3.2 Life cycle impact assessment

As previously mentioned, the overall damage to human health across geographic areas from transportation pollution, defined as public health impact, is estimated using LCA approach. To help readers understand the concept of the public health impact, the details of LCA methodology, used in this study, is given in this part of the thesis.

LCA is an important tool that can assist decision makers for the quantitative analysis of environmental impacts. The impacts occurred during the entire life cycle of a product or a system from raw material acquisition to disposal or recycling stage can be accounted for. This makes LCA known as cradle-to-grave or cradle-to-cradle analysis. As stated in the review by Roy et al., 2009, the concept of LCA was firstly introduced in the 1960s. The understanding and interest to develop an LCA framework have been raised among researchers, practitioners, and international organizations since the 1990s. The complete 4-step process of the generic LCA structure, according to the ISO 14044 standard, is depicted in Fig 3.2, as a result of their efforts to achieve a well-defined a LCA structure (Roy et al., 2009).

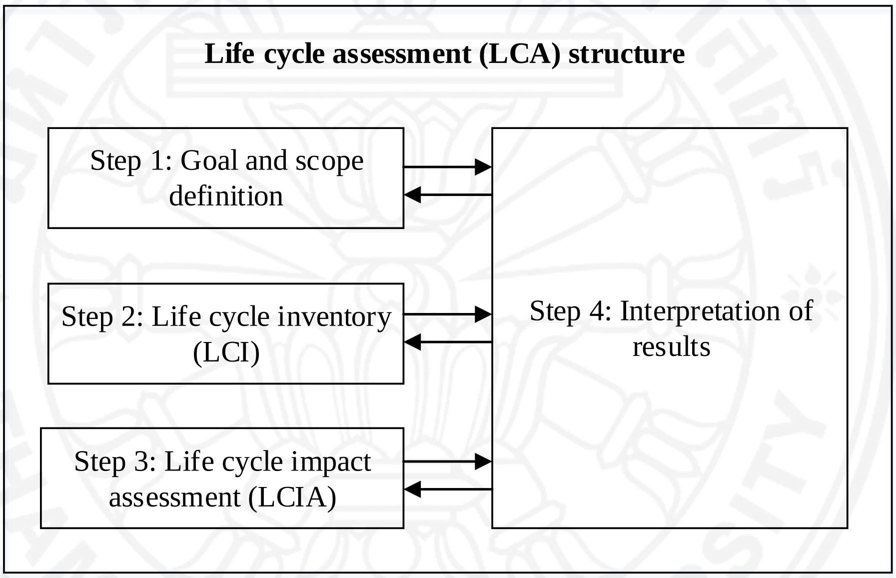

Figure 3.2 Generic LCA structure according to ISO 14040 (ISO, 2006).

The most critical phase is the goal and scope because it provides detailed information about objectives, system boundaries, limitations, and assumptions of a study. After the first stage is determined, different amount of hazardous emissions to the air and consumed natural resources along with this process are collected and analyzed in the LCI phase. This phase is the most time consuming work, as compared to others. The sharing LCI databases of general data (e.g. electricity and coal between customers and suppliers) is necessary. It is considered as a way to reduce the time. In the LCIA phase, the resulting LCI is translated to various environmental impacts. These impacts are classified and quantified in terms of different environmental impact indicators. Indicators are then discussed and compared to similar results obtained in the ISO 14044 to assure adequate and precise conclusions.

The SimaPro software provides a number of methods with their indicators to quantify environmental impacts. There are several LCIA methodologies used for environmental assessment, which include different midpoint and endpoint indicators. These midpoint and endpoint indicators are problem-oriented. They have been used for supply chain network optimization to achieve a strategic supply chain that has a better balance between economic and environmental performance. The three commonly used methodologies in LCA are proposed: CML 2000 baseline, the EI-99 methodologies, and the Recipe. The CML methodology uses multiple midpoint indicators, which represent the direct impact on the environment, such as climate change, acidification, and human toxicity. The EI-99 methodology includes 11 environmental impact categories, which are group into 3 endpoint indicators (damage-oriented indicators). These endpoint indicators reflect the severity of environmental impacts on human health, ecosystems, and resource availability. Environmental impacts are later aggregated into a single score. As highlighted above, the focus on human health damage, as an endpoint impact associated with a SCND, is quite limited. To fill this gap, the ReCiPe LCIA 2008, an improvement on CML and Indicator 99, is proposed in this thesis to quantify human health damage (MTEC, 2015). It is composed 18 midpoint and 3 endpoint indicators for the interpretation of LCI results, as illustrated in Fig 3.3. There are several metrics to quantify human health burden of disease such as years of life lost (YLL), quality adjusted life years (QALYs), disability adjusted life expectancy (DALE), healthy life years (HeaLYs), and disability adjusted life years (DALYs) (Hofstetter & Hammitt, 2002). Among them, the DALY takes into account the number of years of life lost due to premature mortality (YLL) and healthy years of life lost due to disability (YLD). It is considered as one of the most widely used metrics to estimate environmental impacts caused by transportation activities on human health (Murray, 1994).

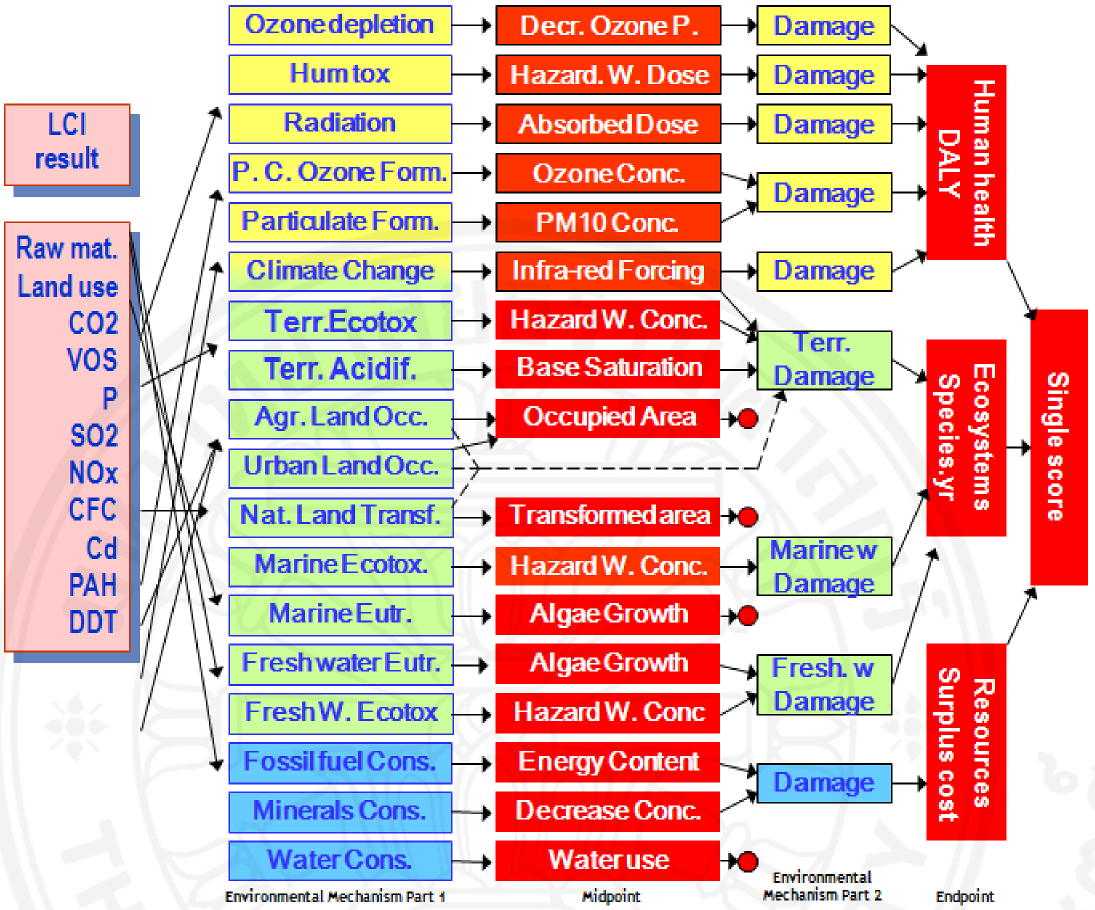

Figure 3.3 Relationship between LCI parameters, midpoint indicators, and endpoint indicators in the Recipe LCIA 2008.
(Adapted from Goedkoop et al., 2009)

A DALY represents lost years of healthy life due to premature death or disability, which ranges from zero for ideal health status to one for total illnesses. Based on the ReCiPe LCIA 2008 endpoint method, the damage to human health takes in to account effects caused by a set of environmental impact categories: climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate formation, and ionizing radiation. In order to mention the public health impact on the affected population, local and regional scale impact categories are taken into account. The damage due to climate change and ozone depletion impact categories is neglected. The total DALYs across the affected population are calculated and used as a measure for public health impact in our multi-objective optimization model, as described in the following chapter.

3.3 Multi-objective optimization

Multi-objective optimization (MO) is a very common tool used to solve various real world engineering and economic problems. The use of MO allows decision makers to simultaneously handle multiple objectives and to gain insight into an optimum set of alternative solutions, known as Pareto optimal sets. In Fig 3.4, a schematic sketch of the Pareto optimal curve with feasible and infeasible solutions is illustrated.

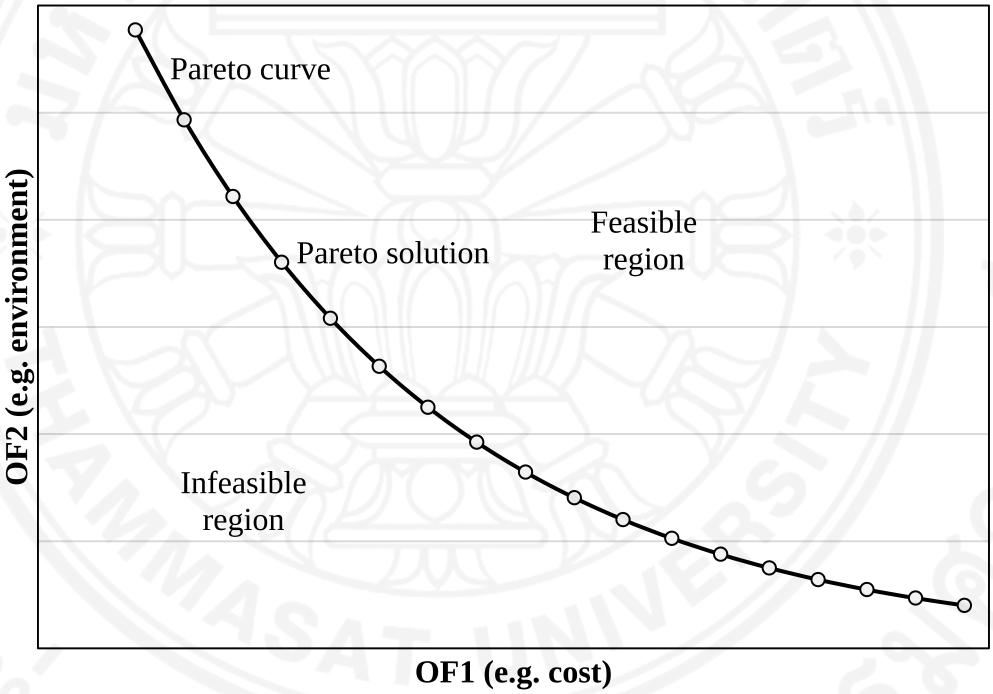

Figure 3.4 Pareto optimal curve for bi-objective optimization problems.

Multi-objective approaches can be seen in various types of problems, such as linear, integer, and mixed integer. Until now, researchers have proposed various methods for solving SCND problems. As stated in Hirche, 1980, the solving methods of multi-objective problems can be categorized into three types: the posteriori, the priory, and the interactive methods, which are based on the characteristics of a decision maker in selecting a suitable solution. For the priory and interactive methods, a decision maker shows their needed solutions before starting the solution process, whereas the interactive method has some interactions between decision makers and a computer. Among aforementioned methods, the posteriori method has gained more interest from decision makers because it can provide an optimal set of alternative solutions before they are needed. Each of these solutions is described as a Pareto optimal solution, which represents a trade-off between conflicting objectives. This means that any improvement in one objective results in the other objectives to be worse. The Pareto frontier, created by linking all Pareto optimal solutions, is a curve that divides the Pareto shape into a feasible and infeasible domain. Afterwards, the best solution for the problem is typically selected, based on decision makers' experience to analyze and evaluate a Pareto optimal set.

This paper generally focuses on finding compromise solutions that can minimize total cost and public health impact, represented by OF1 and OF2, respectively. A common posteriori method, proposed to solve these two conflicting objectives, is the ε constraint method, as firstly suggested by Haimes et al., 1971. Recent studies have also addressed the ε constraint method in yielding a distributed Pareto frontier for a multi-objective problem (Amin & Zhang, 2013; Chaabane et al., 2011; Mele et al., 2011; Pishvaee & Razmi, 2012; Soysal et al., 2014; You & Wang, 2011). According to the method, an objective function is converted from a multi-objective to a single-objective function. In this way, one objective is selected as an objective function, whereas the other constraint is incorporated into the model as an additional constraint. The upper bound, represented by the value of ε, is referred to as the limitation of an additional constraint. As each value of ε is generated, a corresponding Pareto solution along the Pareto frontier, can be found through solving the model including objective function, constraints, and an additional constraint. The model for the problem is formulated as follows.

Minimize: $f(x) = OF1$

Subject to:

Constraints

$OF2 \le \varepsilon$ (additional constraint)

$x \in S$ (feasible region)

Here, OF1 is set as priority for optimization, while OF2 is assigned to an additional constraint. In order to derive an initial value of ε, OF1 and old constraints are considered, and the result found in this case generates the highest amount of DALY (ε). The resulting Pareto frontier is expected to obtain through solving sub-problems, which are created by gradually reducing the value of ε until reaching the lowest value. It is worth noting that each sub-problem leads to a corresponding the Pareto optimal solution.

Chapter 4
Supply chain network design

4.1 Problem description

A three-echelon supply chain, containing collection centers (suppliers), warehouses, and manufacturers, is presented in this chapter. The supply chain is located within a case study city, Can Tho city. The supply chain moves raw materials from collection centers to warehouses, and to a manufacturer, respectively. The diagram showing an example of the supply chain network is depicted in Fig 4.1.

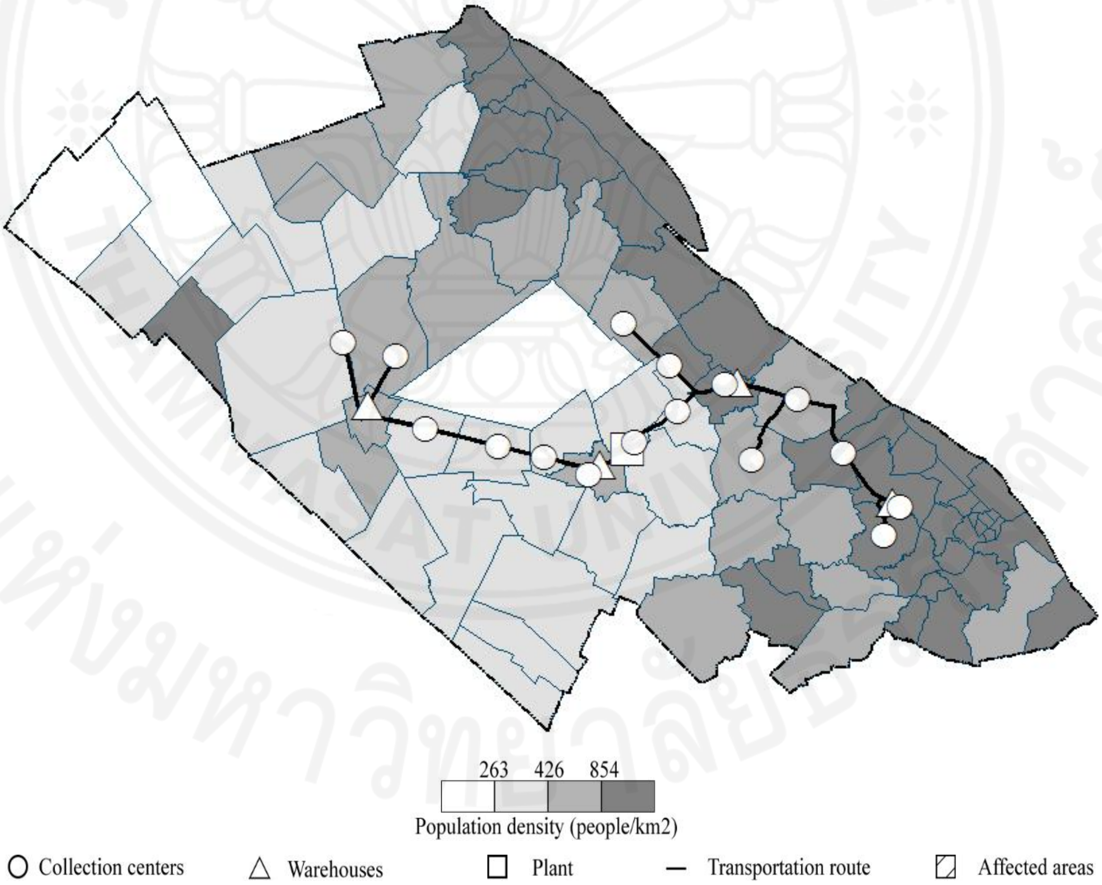

Figure 4.1 Supply chain network case study.

Existing suppliers are responsible for collecting and sorting raw materials located in sub-districts, where fresh raw materials can be easily accessed through a number of surrounding local growers. Although this process allows creating a diversified and high quality raw materials before shipment, each supplier can only supply a limited amount of raw materials for its upstream facilities, including a set of new warehouses and manufacturers. It is worth noting that each of these facilities involves capital investment and storage capacity levels. The design for the location of warehouses in the center of districts aims to achieve convenient transportation. Warehouses are usually used for loading, unloading, and storage of collected raw materials. The amount of raw materials, collected from more than one supplier, is delivered to a selected warehouse, which requires at least 10 percent of its used storage capacity. After that, they are expected to deliver to a manufacturer soon, but it is impossible to keep them in a warehouse longer than a week due to quality consideration. Production regions for manufacturers, located in industrial zones, are responsible for transforming collected raw materials to final products. The demand for final products is assumed to be known in advance and must be fully satisfied by a set of suppliers and warehouses without any shortage.

There exist transportation paths from collection centers to warehouses and from warehouses to manufacturers, but not from collection centers to manufacturers. All transportation is made by truck with a load capacity of 11 tons. It is assumed that all outbound trucks carry empty container from manufacturers to warehouses and from warehouses to collection centers. Then, after picking up raw materials, the inbound trucks return to their starting point with full load of raw materials. The transportation flow is shown in Fig 4.2.

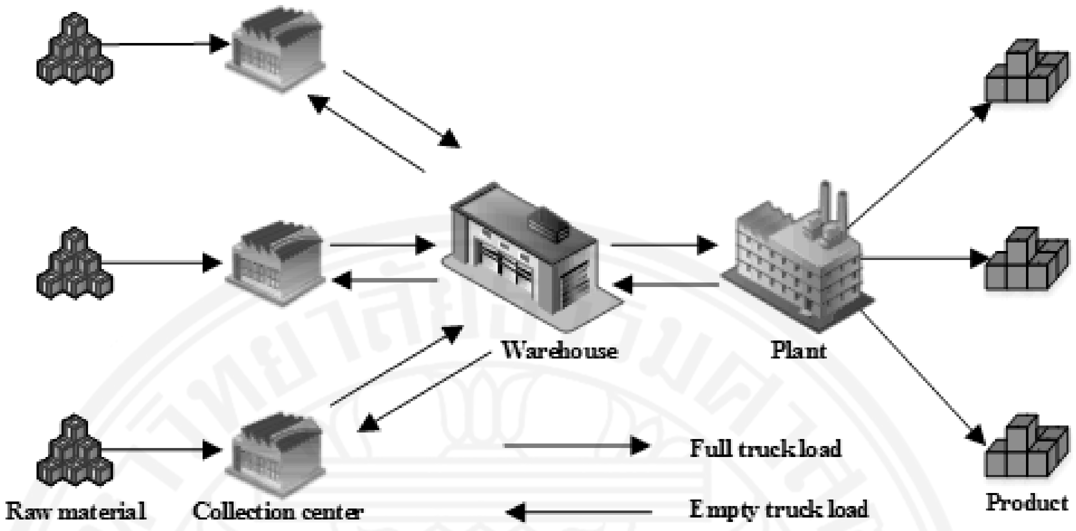

Figure 4.2 Transportation flows of raw materials.

4.2 Assumptions

In addition to the problem description given above, the main assumptions made in this study are elaborated in this section of the thesis.

1. The trucks used to move raw materials from collection centers to warehouses and from warehouses to manufacturers are belong to two different truck fleets.
2. The raw material flow starts from a collection center and finishes at a plant. There are no direct flows between collection centers and plants.
3. The number of warehouses, collection centers, and plants is known.
4. The maximum storage capacity of warehouses is known. However, the lowest storage capacity of a warehouse is assumed to be 10%, to account for the effects of warehouses on the supply chain network.
5. The plant’s demand target level is deterministic and must be satisfied by a set of selected warehouses.
6. The trucks used in the case study are 6-wheel diesel trucks with a maximum payload of 11 tons. Output flows are assumed to be a full load for an 11-ton truck, whereas input flows are always an empty load. There is no loss of raw materials during transportation.

7. The DALY coefficient in this study is based on the damage to human health due to respiratory inorganic impact categories.
8. Total DALYs are estimated based on the number of people living in affected areas.

4.3 Model formulation

A MILP is developed and used here for analyzing a bi-objective: total cost and public health impact minimization. The objective is to determine the optimal set of facility locations, and the flow allocation of raw materials being transported each month. The analysis of the first objective is executed in a way that allows the minimization of total cost, which is composed of transportation cost and facility operating cost. For the second scenario, the DALY coefficient is introduced into the objective function allowing public health impact to be minimized. Other coefficients are necessary in calculating the amount of damage to human health in the second objective function: the number of affected population, the traveling distance of a vehicle, and the vehicle's weight. It must be noted that the two terms, presented for the public health impact, are the DALY of full and empty truck loads.

The formulation of mathematical model is made here in this section. All the notations, including sets, indices, and variables for the proposed model, are defined as follows.

4.3.1 Sets and indices

i: Collection center index i, $i \in I$
j: Warehouse index j, $j \in J$
k: Plant index k, $k \in K$

4.3.2 Variables

$$y_j = \begin{cases} 1, \text{ if a warehouse is located in potential point j} \\ 0, \text{ otherwise} \end{cases}$$

$$z_k = \begin{cases} 1, \text{ if a plant is located in potential point k} \\ 0, \text{ otherwise} \end{cases}$$

x_{ijk} = Amount of raw materials (tons) per month transported from i to k across j

n_{ijk} = Number of times per month, raw materials transported from i to k across j

4.3.3 Parameters

c_{ijk}	Transportation cost to deliver raw materials from i to k across j
p_{ijk}	Number of people affected by transportation activities from i to k across j
d_{ijk}	Distance from i to k across j
f_j	Construction cost of warehouse j
f_k	Construction cost of plant k
sc_i	Storage capacity of collection center i (tons) can deliver per month
sw_j	Storage capacity of warehouse j (tons) can receive per month
sp_k	Amount of raw materials (tons) required by plant k per month
t	Truck carrying weight (tons)
α_1, α_2	DALY coefficient for full and empty truck loads

4.3.4 Mathematical modeling

In this research, the MILP model is composed of two objective functions: cost minimization (OF1) and public health impact minimization (OF2). The total cost of supply chain network (OF1) is equal to the construction cost of warehouses and plants, and transportation cost. Transportation cost is estimated based on the travelling distance and number of times that raw materials are transported between facilities. The first objective is formulated as follows.

$$Min\, OF_1 = \sum_{j} f_j y_j + \sum_{k} f_k z_k + \sum_{ijk} c_{jk} n_{ijk} \qquad (1)$$

The public health impact (OF2), caused by transportation activities in the supply chain network, is estimated based on the total DALYs associated with full and empty truck loads. The factors affecting the total DALYs are the number of affected population, truck carrying weights, travelling distance, and the delivery frequency between facilities. It is worth noting that the unit of DALY coefficient is person/t.km for full truck load, whereas it is person/km for empty truck load. Therefore, the second objective and all constraints are formulated as follows.

$$Min\, OF_2 = \sum_{ijk} p_{ijk} q_{ijk} n_{ijk} t \alpha_1 + \sum_{ijk} p_{ijk} d_{ijk} n_{ijk} \alpha_2 \qquad (2)$$

Equation (3) ensures that collection center i is selected only if its output flow is less than its capacity.

$$\sum_{jk} x_{ijk} \le sc_i \qquad \forall i \in I \qquad (3)$$

Equation (4) ensures that the total flow of raw materials to warehouse j is at least h (%) of the warehouse’s storage capacity.

$$\frac{1}{2} sw_j y_j \le \sum_{ik} x_{ijk} \le sw_j y_j \qquad \forall j \in J \qquad (4)$$

Equation (5) makes sure that outbound trucks deliver raw materials with its full carrying weight of t (tons).

$$x_{ijk} = n_{ijk} t \qquad \forall i, j, k \in I, J, K \tag{5}$$

Constraint (6) enforces that the total amount of raw materials delivered from all warehouses to a plant is matched with the plant's demand.

$$\sum_{ij} x_{ijk} = z_k sp_k \qquad \forall k \in K \tag{6}$$

Equation (7) states that only one potential location of plant k is selected.

$$\sum_{k} z_k = 1 \qquad \forall k \in K \tag{7}$$

Constraint (8) - (11) represent the integrality, non-negativity, and binary restrictions imposed upon the decision variables.

$$x_{ijk} \geq 0 \tag{8}$$

$$n_{ijk} \geq 0 \qquad \text{Integer} \tag{9}$$

$$y_j \in \{0,1\} \tag{10}$$

$$z_k \in \{0,1\} \tag{11}$$

The proposed model allows decision makers to determine the total cost and to measure the public health impact caused by transportation activities. The additional information obtained from solving the formulated mathematical model include the amount of products and the number of times per month that raw materials are transported from supplier i to manufacturer k across warehouse j.

4.4 Case study

The proposed model is illustrated through a supply chain case study in Can Tho, Vietnam. First, the information about the city is given here. Can Tho is one of the five largest metropolitan areas in Vietnam, with gradually population growth and a wide range of urban issues. The city covers a total area of 1,390 km^2, which is divided into 9 districts and 85 sub-districts, ranging in size from 3.4 to 71.39 km^2. The inner peripheries of Can Tho City include 5 districts, which are classified into urban areas: Ninh Kieu, Binh Thuy, Cai Rang, O Mon, and Thot Not. The outer peripheries of Can Tho City include the rest of the districts, which are classified as rural areas: Phong Dien, Co Do, Vinh Thanh, and Thoi Lai. Along with a continuous movement of people from rural to urban areas, the percentage of urban population in Can Tho moderately grew from 59% in 2008 to 66% in 2011. Can Tho's population grew at a rate of 9.7%, with a population of 1.25 mil people and a population density of 854 people/km^2, which is the highest in the Mekong Delta region (World Bank, 2014). The historical data is evidence for the rapid urbanization in Can Tho city, as illustrated in Fig 4.3.

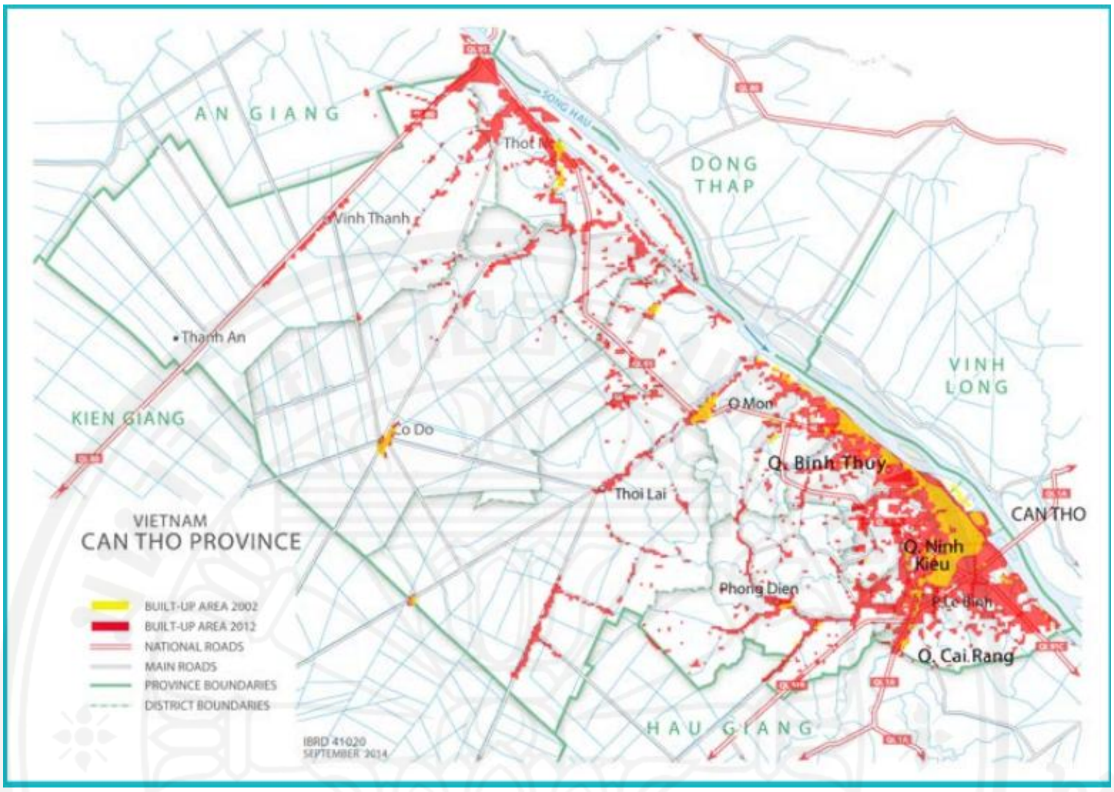

Figure 4.3 Urbanization in Can Tho city, Vietnam.
(Adapted from Pham et al., 2010)

Can Tho has a convenient location and diversity of agricultural products, which creates advantages for companies constructing their supply chain networks of agricultural products. The city is located in the epicenter of the Mekong Delta region, with 6 national highways connecting the city to the rest of the country. The main national highway No.1 connects some provinces of the region to Ho Chi Minh City, which is the largest metropolitan area of Vietnam. Therefore, the demand for cargo, transported by vehicle to and from the city, is becoming greater in proportion, as the number of people increases. It is worth noting that the total area of the region only accounts for 12.3% of the total area of Vietnam. However, it is considered as a source of agricultural products, accounting for 51% of total annual output in 2013. Specifically, the annual output of Can Tho gradually increased from 1,201.7 million metric tons to 1,376.5 million metric tons in the period, 2010 - 2013 (General Statistics Office of Viet Nam, 2014). The location of Can Tho city is illustrated in Fig 4.4.

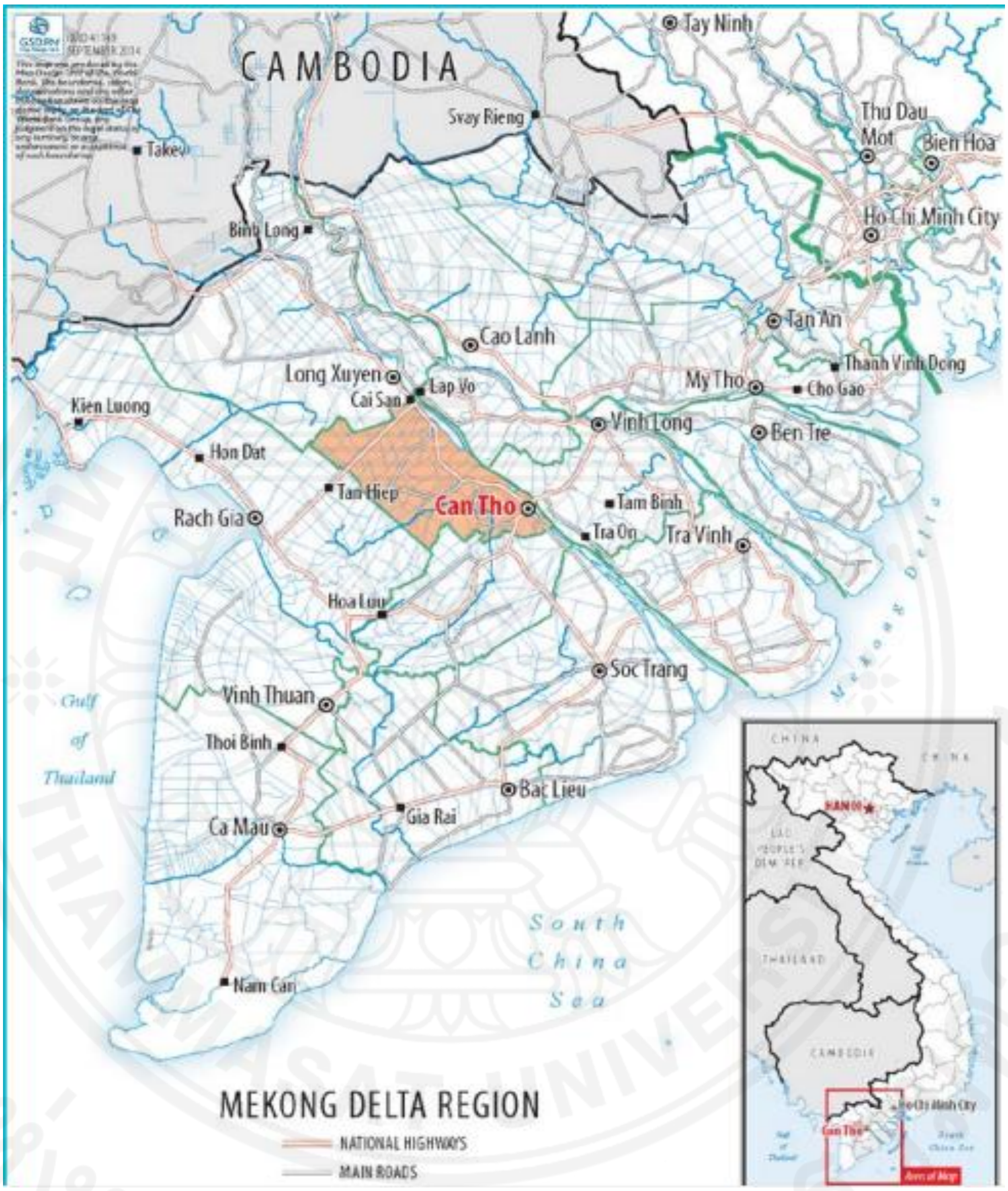

Figure 4.4 Location of Can Tho city in the Mekong Delta region.
Adapted from (World Bank, 2014)

Rapid population growth and socio-economic development have put lots of pressure on the natural and built environments. Therefore, the city has been the study on climate resilience, disaster risk management, transport, water and sanitation, and broader urban development. In this thesis, a supply chain network, located in Can Tho city, is presented in order to illustrate how to assess the public health impact on affected population across geographical areas. The details of the supply chain network are described as follows.

ABC Company, a pomelo juice producer, wants to establish its supplier network in Can Tho city, Vietnam. The company plans to get its supply from local pomelo growers in Can Tho city. There are 9 districts and 85 sub-districts in Can Tho city, 66 of which can serve as the company’s sources of pomelos. Throughout the year, the total pomelo productivity level of these districts is by far greater than the amount needed by the company. Therefore, the company plans on obtaining pomelos from some of the districts just enough to fulfill its demand at the lowest possible transportation cost.

The company will only construct warehouses in some districts, which enable them to fulfill their demand with the lowest transportation cost. In the selected districts, pomelos grown by local growers in each sub-district are collected at collection centers. Then, supply from all the collection centers in a district is delivered to the district's warehouse. After that, pomelos, stored in all warehouses, are sent to the company's soon-to-be-built plant. There are four potential locations in Can Tho city for the plant. The company wants to design their supply network, the selection of supply districts and the plant location, to minimize the transportation cost. Besides the cost aspect, the company also wants to minimize the health impact on local residents caused by the transportation activities of their supply chain network.

In Table 4.1, the distances between warehouses and plant locations are shown. The construction cost and the storage capacity of each warehouse are given. The storage capacity of a warehouse is 198 tons per month. The total storage capacity of all warehouses is 1,782 tons, which is equivalent to the plant’s monthly demand. The construction cost of a plant is $600,000. The construction cost of a warehouse is $20,000. All plant locations on the map of Can Tho city are depicted in Fig 4.5.

Table 4.1 Traveling distance between warehouse and plant locations.

Warehouse	**Distance (in km) to plant**			
	Plant A	**Plant B**	**Plant C**	**Plant D**
Ninh Kieu	13.2	46.99	45.1	25.41
Binh Thuy	10.86	43.67	41.74	22.09
Cai Rang	19.2	52.99	51.05	31.41
O Mon	8.44	29.92	27.99	8.34
Thot Not	34.78	7.29	21.17	29.23
Phong Dien	19.63	47.38	45.44	25.79
Co Do	34.47	30.35	1.96	19.65
Thoi Lai	18.84	34.87	17.56	2.09
Vinh Thanh	54.57	16.22	19.01	33.71

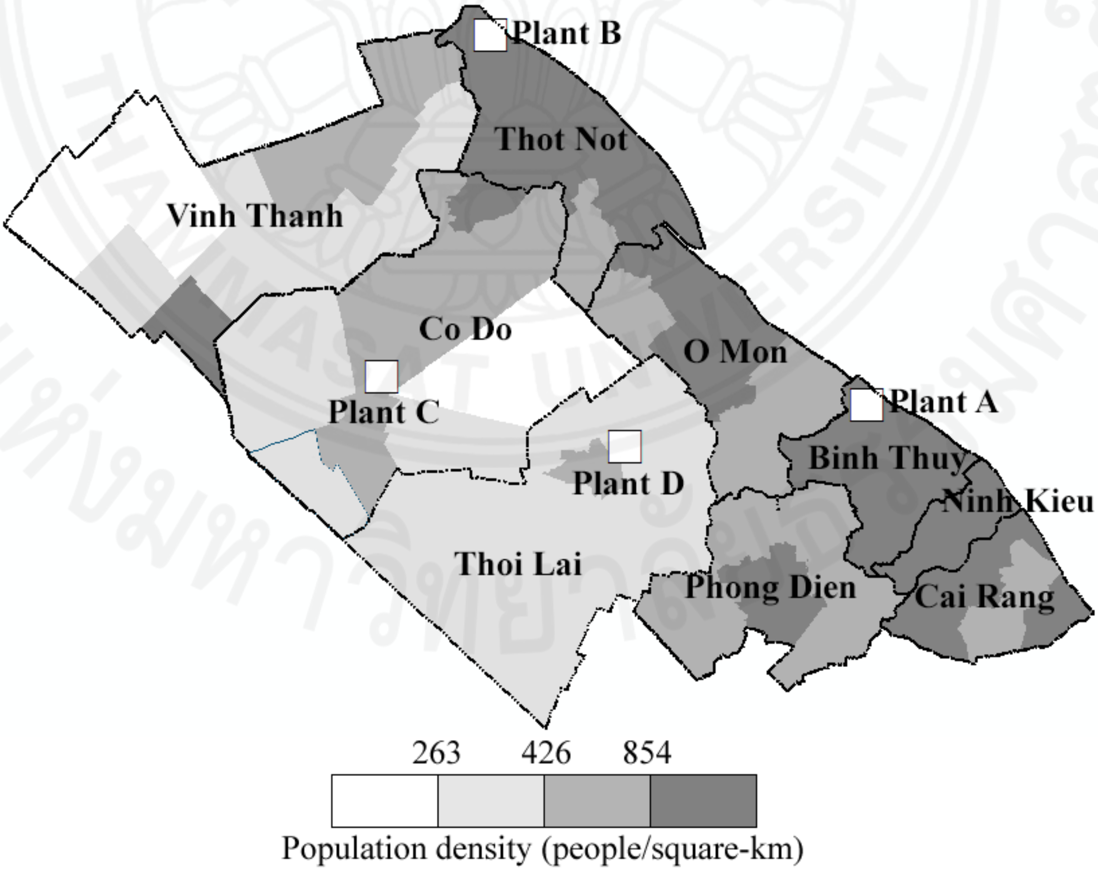

Figure 4.5 Potential locations of manufacturing plant in Can Tho city.

Chapter 5
Results & Discussions

Due to the simplicity of the case study, the solutions are found via the use of CPLEX version 12.0 optimization software with minimal computational time. There are 12 sub-problems involved in the optimization of the case study network. A Pareto optimal front is obtained by joining 12 Pareto optimal solutions, as depicted in Fig 5.1. The obtained Pareto frontier is valuable for decision makers, because it shows the overview of the trade-offs between cost and public health impact.

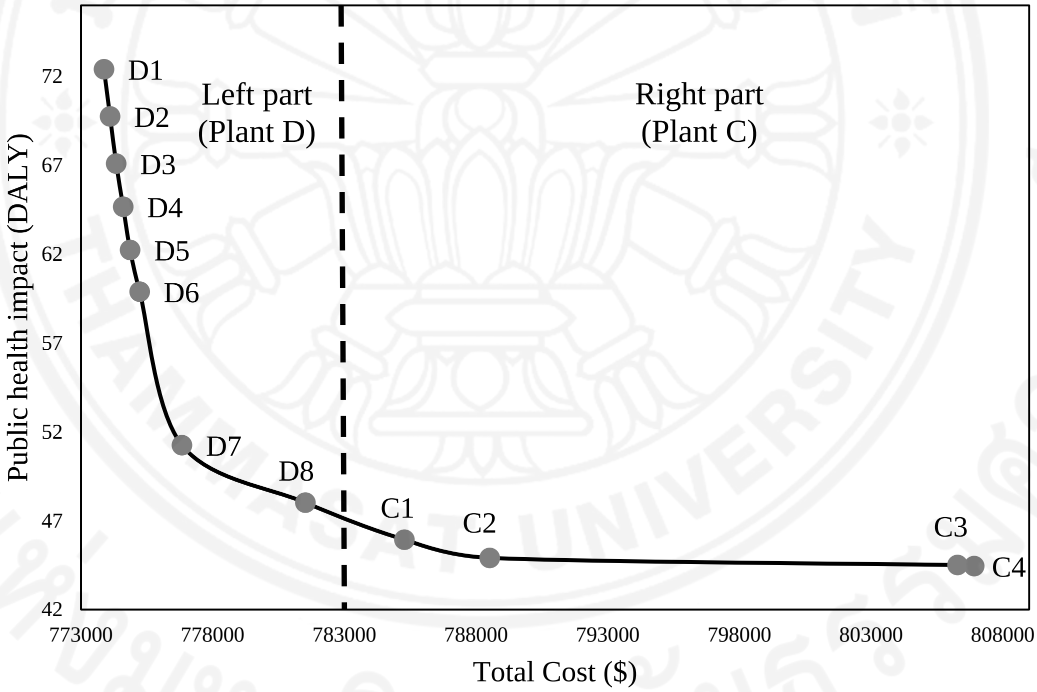

Figure 5.1 Pareto optimal curve of total cost and public health impact.

According to Fig 5.1, the Pareto front can be divided into two parts. The left part of the curve corresponds to the solutions where location D is selected as the optimal location for plant. In this part, substantial reduction in human health impact can be achieved at a minimal increase in cost. For the right part of the curve, location C is selected as the optimal location for plant. In this part, the level of public health impact is lower than that of the right part. However, the total cost is much higher due to the additional traveling distance needed for the truck fleet to avoid the densely populated areas.

To visualize the overall picture of the tradeoff, the first solution (D1) and the last Pareto solutions (C4) can be viewed as the upper and lower bounds of public health impact, respectively. Then, it can be observed from the computational results that an 12.2% increase in transportation cost can be compensated by about 62.9% reduction in the public health impact. More computational results, representing the relationship between transportation cost and public health impact, are listed in Table 5.2.

Table 5.1 Trade-offs between transportation cost and public health impact.

Solution	**Increase in Transportation cost (%)**	**Decrease in Public health impact (%)**
D2 vs C4	12	56.9
D3 vs C4	11.8	50.9
D4 vs C4	11.5	45.4
D5 vs C4	11.3	40
D6 vs C4	10.9	34.7
D7 vs C4	9.4	15.3
D8 vs C4	9.4	15.3
C1 vs C4	1.5	3.4
C3 vs C4	0.6	0.1

Different solutions mean different supply chain configurations; different locations and number of warehouses and collection centers selected to supply pomelo to the optimal plant location. More details of these trade-offs are discussed as follows.

+ *Left part (Low cost's selection):* There are 8 Pareto optimal solutions including D1, D2, D3, D4, D5, D6, D7, and D8. Each solution on the left part of the Pareto frontier corresponds to the selection of Plant D in Thoi Lai district. This plan's location is close to the pomelo sources in Thoi Lai, Co Do, Binh Thuy, O Mon, and Phong Dien districts, as depicted in Fig 5.2. The shorter travelling distance between facilities results in a lower logistics cost, as compared to those on the right part. However, a significant reduction in public health impact can be seen through the comparison between solution D1 and D8. Although 8.2% of the transportation cost increases, the public health impact decreases by 34 %. This difference is due to the large number of people affected by transportation activities across geographical areas in O Mon and Binh Thuy districts.

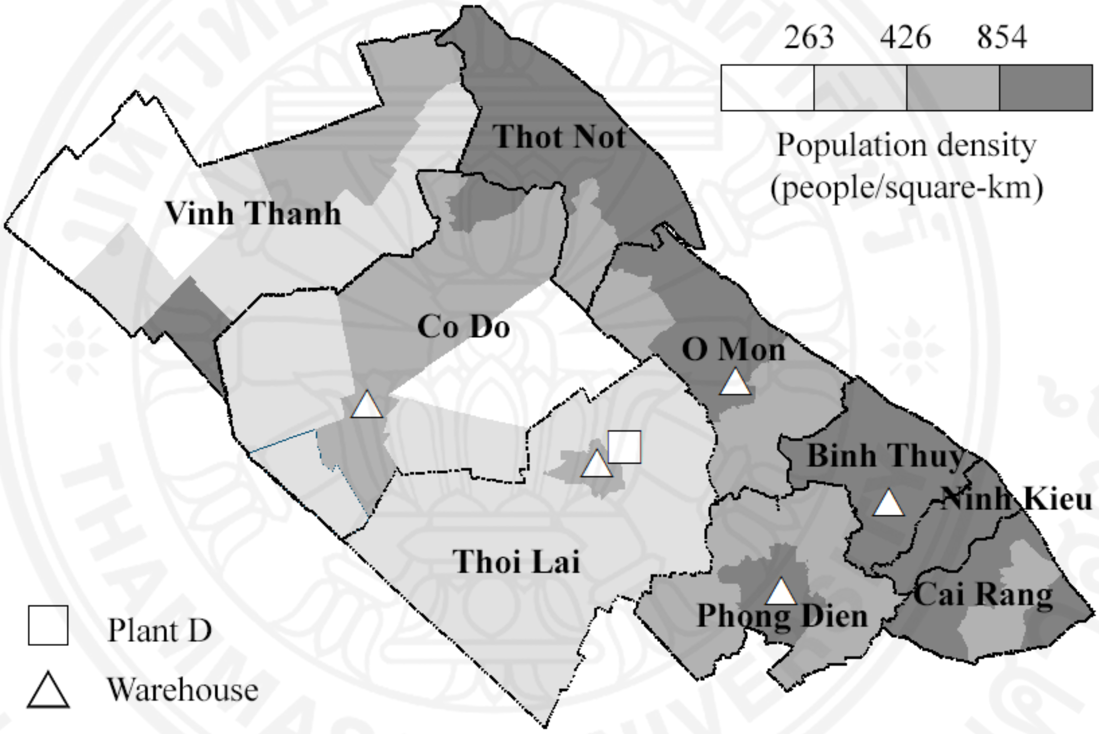

Figure 5.2 Plant and warehouse locations correspond to solution D1-D8.

+ *Right part (Low public health impact’s selection):* This part is composed of 4 Pareto optimal solutions: C1, C2, C3, and C4. Each of which corresponds to the selection of Plant C in Co Do district. This district and its neighboring districts, such as Vinh Thanh, Thoi Lai, O Mon, and Thot Not, are the closest pomelo sources to Plant C, as illustrated in Fig 5.3. The difference between solution C1 and C4 is a significant reduction in the total cost. The use of only 4 warehouses to serve as pomelo sources for Plant C is the main cause of the change in the total cost. Specifically, there are 4 warehouses for solution C1 and solution C2, whereas there are 5 warehouses for solution C3 and solution C4.

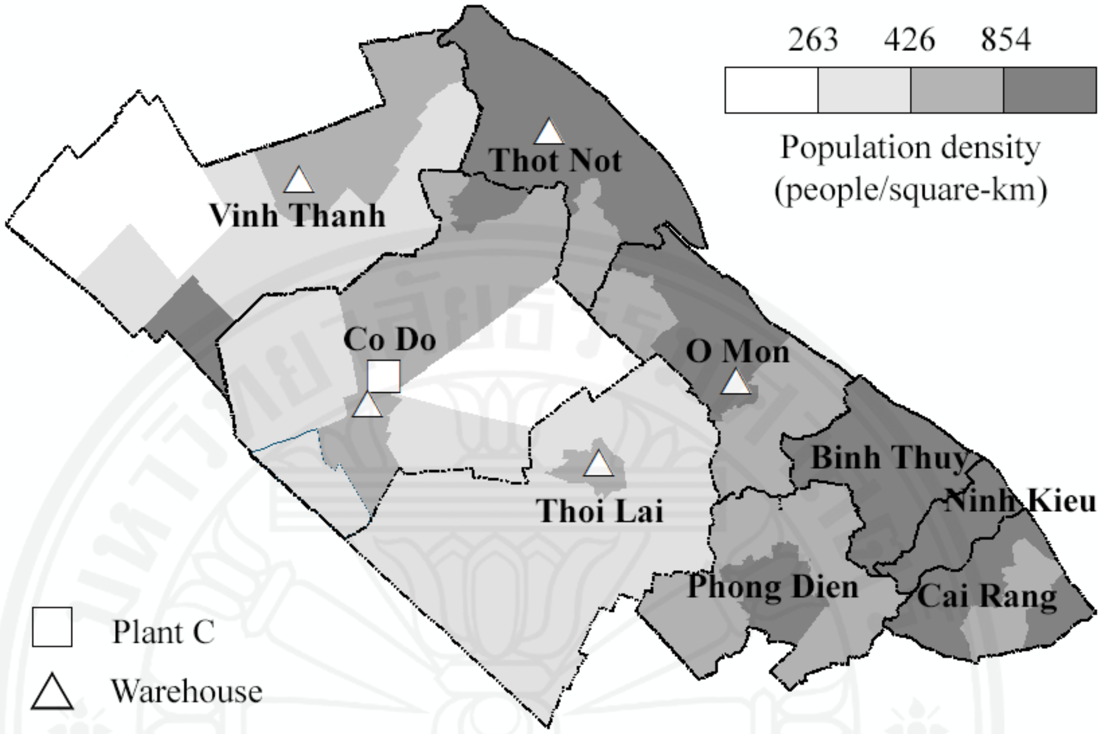

Figure 5.3 Plant and warehouse locations correspond to solution C1-C4.

By comparing the Pareto solutions along the curve in Fig 5.1, we can determine a good solution that can lower the total cost and the public health impact. The Pareto optimal solutions on the left part tend to be much more promising than other solutions on the right part. From all the solutions on the left part, solution D8 appears to be the most promising solution due to the good balance between the two objectives. The total cost of solution D8 is the highest, but the resulting public health impact is the lowest among the solutions on the left part. The public health impact of solution D8 is 8% higher than that of solution C4. The transportation cost of solution D8 is 8.1% higher than that of solution D1. The supply chain networks, corresponding to solution D1 and D8, are illustrated in Fig 5.4a and Fig 5.4b, respectively.

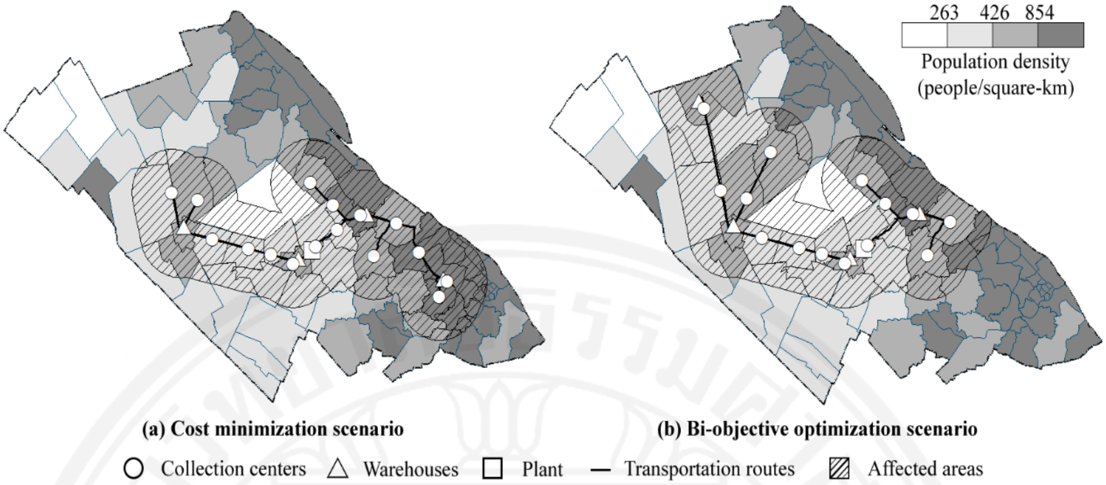

Figure 5.4 Optimal supply chain network configurations of solution D1 and D8.

** Cost objective (solution D1)*

According to the studying results shown in Table 5.2 and Fig 5.5, the supply network is composed of 4 warehouses, which are served as pomelo sources for plant D in Thoi Lai district. Two of which, located closely to plant D, fully utilize their storage capacity in order to get more benefit from lower transportation cost. Besides the transportation cost, the strategic decisions are considered based on the availability of pomelo from collection centers. This can be seen in the transportation route TT Thoi Lai - Thoi Lai. Although the collection center in TT Thoi Lai has a shorter distance to a warehouse in Thoi Lai district, it is not selected as the supplier. This is because its storage capacity is lower than truck requirement (11 tons). The close proximity of facility locations can lower the total cost and the public health impact.

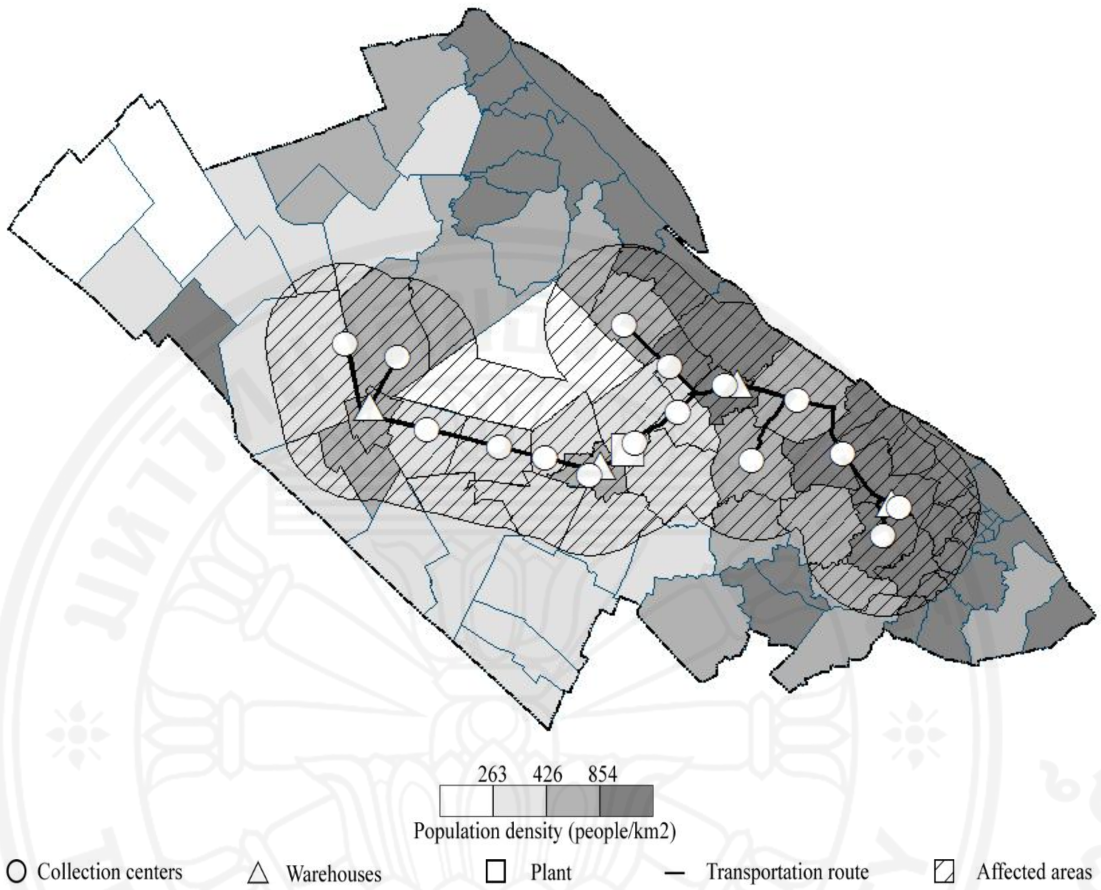

Figure 5.5 Supply chain network of cost minimization.

Table 5.2 Optimal transportation route and the corresponding transportation cost and health impact for solution D1.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total Trans. Cost ($)**	**Health Impact* Full (DALYs)**
Tan Thanh - Thoi Lai - Plant D	88	3,816	0.76
TT Thoi Lai - Thoi Lai - Plant D	77	2,114	0.38
Xuan Thang - Thoi Lai - Plant D	33	1,695	0.35
L. Tuyen - Binh Thuy - Plant D	66	15,306	23.02
T. A. Dong - Binh Thuy - Plant D	44	10,604	15.66
Long Hoa - Binh Thuy - Plant D	11	2,263	3.38
Dong Hiep - Co Do - Plant D	44	11,532	5.04
NT Co Do - Co Do - Plant D	33	7,647	3.15
Thanh Phu - Co Do - Plant D	33	6,936	2.82
Dong Thang - Co Do - Plant D	33	7,239	2.87
Long Hung - O Mon - Plant D	44	6,884	4.45
Phuoc Thoi - O Mon - Plant D	44	4,880	2.87
Thoi Hoa - O Mon - Plant D	44	5,340	3.11
C. V. Liem - O Mon - Plant D	33	2,766	1.45
Truong Lac - O Mon - Plant D	33	4,848	3.09
Total	**660**	**93,870**	**72.4**

(*) Health impact shown in the table is defined as the total DALYs of empty and full truck load of 11 tons of pomelo travelled from the selected collection centers to Plant D located in Thoi Lai district across the selected warehouses.

** Bi-objective (solution D8)*

Another interesting point is to explore factors affecting the optimal plant and warehouse locations when the problem is solved under both cost and public health impact objectives. To explore this, we investigate solution D8 whose supply chain configuration and transportation flows are depicted in Fig 5.6 and Table 5.3, respectively.

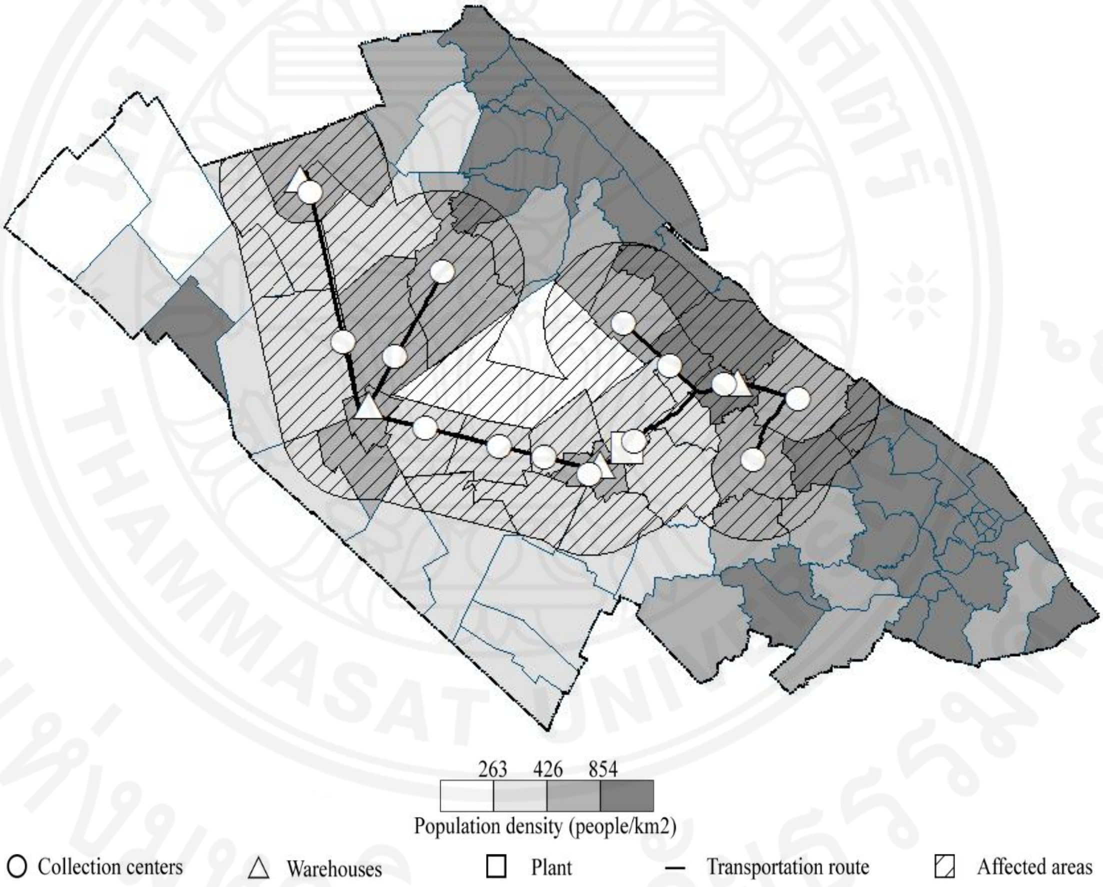

Figure 5.6 Supply chain network correspond to solution D8.

Table 5.3 Optimal transportation route and the corresponding transportation cost and public health impact.

Selected Trans. Route (C.center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact***
		Trans. Cost ($)	**Full (DALYs)**
Tan Thanh - Thoi Lai - Plant D	88	3,816	0.76
TT Thoi Lai - Thoi Lai - Plant D	77	2,114	0.38
Xuan Thang - Thoi Lai - Plant D	33	1,695	0.35
TT V. T. - Vinh Thanh - Plant D	66	21,312	10.69
Dong Hiep - Co Do - Plant D	66	17,298	7.56
Trung Hung - Co Do - Plant D	33	8,745	4.45
NT Co Do - Co Do - Plant D	33	7,647	3.15
Thanh Phu - Co Do - Plant D	33	6,936	2.82
Dong Thang - Co Do - Plant D	33	7,239	2.87
Long Hung - O Mon - Plant D	44	6,884	4.45
Phuoc Thoi - O Mon - Plant D	44	4,880	2.87
Thoi Hoa - O Mon - Plant D	44	5,340	3.11
C. V. Liem - O Mon - Plant D	33	2,766	1.45
Truong Lac - O Mon - Plant D	33	4,848	3.09
Total	**660**	**101,520**	**48**

(*) Health impact shown in the table is defined as the total DALYs of empty and full truck load of 11 tons of pomelo travelled from the selected collection centers to plant D located in Thoi Lai district across the selected warehouses.

The supply chain network of solution D8 includes 14 collection centers, which supply pomelo to four warehouses, located in Thoi Lai, Vinh Thanh, Co Do, and O Mon districts, and to Plant D. The main factor, affecting the optimal plant and warehouse locations, is the population density along each segment of the transportation routes. The overall health damage is significantly affected by the distance and population density of areas along the selected transportation routes, as demonstrated by the data in Table 5.3. The use of transportation route from Thanh Phu to WH Co Do generates slightly lower the public health impact than that of the route from Truong Lac to WH O Mon, although the former has more travelling distance than the latter. This is due to the population density of O Mon district that is much greater than that of Co Do district. Without the variation in population density across different sub-districts, the selection of facility location is made solely based on the traveling distance.

The affected area in each district and the number of affected population are shown in Table 5.4. At the demand level of 660 tons per month, the company's pomelo supply chain network can affect as much as 31% of Can Tho city's residential population. The affected area accounts for about 45% of the entire city. The district with a small affected area such as Thot Not can have a large public health burden due their high population density.

Table 5.4 Area and the number of people affected by transport emissions.

District	**Affected area**		**Total areas**	
	Area (km^2)	**Population**	**Area (km^2)**	**Population**
Ninh Kieu	0	0	29.09	20,8714
Binh Thuy	18.5	20,890	70.71	113,447
Cai Rang	0	0	67.42	89,259
O Mon	117.4	119,758	125.1	128,170
Thot Not	9	5,852	125.88	168,661
Phong Dien	15.4	12,418	124.97	109,245
Co Do	250.6	108,494	326.66	144,882
Thoi Lai	127	45,221	266.81	91,349
Vinh Thanh	100.2	43,975	296.26	122,699
Total	**638.1**	**356,608**	**1,432.9**	**1,176,426**

Chapter 6
Conclusions & Recommendations

6.1 Conclusions

This thesis presents a novel approach for public health impact assessment in a SCND problem. The approach makes use LCA approach, GIS technique, and optimization modeling. The use of ArcGIS mapping software can help urban planners spatially analyze the distribution of public health impact in a city. This includes the location of affected areas and the number of affected population in each district. Bi-objective mathematical model is formulated and solved using multi-objective solving method, allowing the design of supply chain network with a consideration of both economic and public health impact aspects. The case study of Can Tho city is used to illustrate the assessment approach, the calculation procedures, and the rational used to determine the network configuration with favorable economic and environmental performances.

From the analysis, the travelling distance between facilities appears to be one of the main factors affecting the transportation cost and public health impact. However, a shorter transportation distance does not always lead to a lower public health impact. Because when traveling through densely populated area, air pollution from vehicles can cause health effect to large number of people. In this case, additional traveling distance required to avoid populated area may be needed for less public health burden. In our case study, with public health impact consideration, collection centers and warehouses located in the southern areas of Can Tho city are selected due to the lower population density compared to other parts of the city.

Regarding the human health impact assessment, the human health damage is assessed using the Recipe 2008 Endpoint LCIA method, and expressed in the unit of DALYs. The use of DALYs allows us to assess the potential population exposures to transport-related air pollution. In the case study, the public health impact under cost minimization objective is 72.4 DALYs. It means that the entire population of Can Tho city loses 72.4 of their healthy life years, due to the transport pollution of the supply chain network. It must be noted that this number of loss year can be increased to 504.2, if the impact due to climate change and ozone depletion is included. It is expected that the result of this thesis create a better understanding among urban planners and decision makers on how SCND affects people in terms of their health.

6.2 Recommendations

The primary area for future research involves how to improve the accuracy of the estimation of affected population. The current assumption of uniform population density within each sub district may result in a distorted estimate of the number of population affected by transport pollution, especially for the areas where population is clearly concentrated along the main transportation routes or in certain parts of the area. The use of GIS software with a higher detail of geographical data is necessary for a more accurate estimate.

The current MILP model can be reformulated using two-dimensional decision variables. This will result in much less number of decision variables. The amount of data concerning the size of the affected area and the number of affected population along transportation routes will also be reduced considerably.

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Appendix A

Table A.1. Optimal transportation route and the corresponding transportation cost and health impact for solution D2.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact**
		Tran. Cost ($)	**Full (DALYs)**
Tan Thanh - Thoi Lai - Plant D	88	3,816	0.76
TT Thoi lai - Thoi Lai - Plant D	77	2,114	0.38
Xuan Thang - Thoi Lai - Plant D	33	1,695	0.35
Dong Hiep - Co Do - Plant D	55	14,415	6.3
NT Co Do - Co Do - Plant D	33	7,647	3.15
Thanh Phu - Co Do - Plant D	33	6,936	2.82
Dong Thang - Co Do - Plant D	33	7,239	2.87
L. Tuyen - Binh Thuy - Plant D	66	15,306	23.02
Long Hoa - Binh Thuy - Plant D	11	2,263	3.38
T. A. Dong - Binh Thuy - Plant D	33	7,953	11.75
Long Hung - O Mon - Plant D	44	6,884	4.45
Phuoc Thoi - O Mon - Plant D	44	4,880	2.87
Thoi Hoa - O Mon - Plant D	44	5,340	3.11
C. V. Liem - O Mon - Plant D	33	2,766	1.45
Truong Lac - O Mon - Plant D	33	4,848	3.09
Total	**660**	**94,102**	**69.75**

Table A.2. Optimal transportation route and the corresponding transportation cost and health impact for solution D3.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact**
		Trans. Cost ($)	**Full (DALYs)**
Tan Thanh - Thoi Lai - Plant D	88	3,816	0.76
TT Thoi lai - Thoi Lai - Plant D	77	2,114	0.38
Xuan Thang - Thoi Lai - Plant D	33	1,695	0.35
Dong Hiep - Co Do - Plant D	66	17,298	7.56
NT Co Do - Co Do - Plant D	33	7,647	3.15
Thanh Phu - Co Do - Plant D	33	6,936	2.82
Dong Thang - Co Do - Plant D	33	7,239	2.87
L. Tuyen - Binh Thuy - Plant D	66	15,306	23.02
Long Hoa - Binh Thuy - Plant D	11	2,263	3.38
T. A. Dong - Binh Thuy - Plant D	22	5,302	7.83
Long Hung - O Mon - Plant D	44	6,884	4.45
Phuoc Thoi - O Mon - Plant D	44	4,880	2.87
Thoi Hoa - O Mon - Plant D	44	5,340	3.11
C. V. Liem - O Mon - Plant D	33	2,766	1.45
Truong Lac - O Mon - Plant D	33	4,848	3.09
Total	**660**	**94,334**	**67.09**

Table A.3. Optimal transportation route and the corresponding transportation cost and health impact for solution D4.

Selected Trans. Route (C. center - Warehouse - Plant)	Quantity (Tons/month)	Total	Health Impact
		Trans. Cost ($)	Full (DALYs)
Tan Thanh - Thoi Lai - Plant D	88	3,816	0.76
TT Thoi lai - Thoi Lai - Plant D	77	2,114	0.38
Xuan Thang - Thoi Lai - Plant D	33	1,695	0.35
Dong Hiep - Co Do - Plant D	66	17,298	7.56
Trung Hung - Co Do - Plant D	11	2,915	1.49
NT Co Do - Co Do - Plant D	33	7,647	3.15
Thanh Phu - Co Do - Plant D	33	6,936	2.82
Dong Thang - Co Do - Plant D	33	7,239	2.87
L. Tuyen - Binh Thuy - Plant D	66	15,306	23.02
Long Hoa - Binh Thuy - Plant D	11	2,263	3.38
T. A. Dong - Binh Thuy - Plant D	11	2,651	3.91
Long Hung - O Mon - Plant D	44	6,884	4.45
Phuoc Thoi - O Mon - Plant D	44	4,880	2.87
Thoi Hoa - O Mon - Plant D	44	5,340	3.11
C. V. Liem - O Mon - Plant D	33	2,766	1.45
Truong Lac - O Mon - Plant D	33	4,848	3.09
Total	**660**	**94,598**	**64.66**

Table A.4 Optimal transportation route and the corresponding transportation cost and health impact for solution D5.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact**
		Trans. Cost ($)	**Full (DALYs)**
Tan Thanh - Thoi Lai - Plant D	88	3,816	0.76
TT Thoi lai - Thoi Lai - Plant D	77	2,114	0.38
Xuan Thang - Thoi Lai - Plant D	33	1,695	0.35
Dong Hiep - Co Do - Plant D	66	17,298	7.56
Trung Hung - Co Do - Plant D	22	5,830	2.97
NT Co Do - Co Do - Plant D	33	7,647	3.15
Thanh Phu - Co Do - Plant D	33	6,936	2.82
Dong Thang - Co Do - Plant D	33	7,239	2.87
L. Tuyen- Binh Thuy - Plant D	66	15,306	23.02
Long Hoa - Binh Thuy - Plant D	11	2,263	3.38
Long Hung - O Mon - Plant D	44	6,884	4.45
Phuoc Thoi - O Mon - Plant D	44	4,880	2.87
Thoi Hoa - O Mon - Plant D	44	5,340	3.11
C. V. Liem - O Mon - Plant D	33	2,766	1.45
Truong Lac - O Mon - Plant D	33	4,848	3.09
Total	**660**	**94,862**	**62.23**

Table A.5. Optimal transportation route and the corresponding transportation cost and health impact for solution D6.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact**
		Trans. Cost ($)	**Full (DALYs)**
Tan Thanh - Thoi Lai - Plant D	88	3,816	0.76
TT Thoi lai - Thoi Lai - Plant D	77	2,114	0.38
Xuan Thang - Thoi Lai - Plant D	33	1,695	0.35
Dong Hiep - Co Do - Plant D	66	17,298	7.56
Trung Hung - Co Do - Plant D	33	8,745	4.45
NT Co Do - Co Do - Plant D	33	7,647	3.15
Thanh Phu - Co Do - Plant D	33	6,936	2.82
Dong Thang - Co Do - Plant D	33	7,239	2.87
L. Tuyen - Binh Thuy - Plant D	55	12,755	19.18
L. Hoa - Binh Thuy - Plant D	11	2,263	3.38
Long Hung - O Mon - Plant D	44	6,884	4.45
Phuoc Thoi - O Mon - Plant D	44	4,880	2.87
Thoi Hoa - O Mon - Plant D	44	5,340	3.11
C. V. Liem - O Mon - Plant D	33	2,766	1.45
Truong Lac - O Mon - Plant D	33	4,848	3.09
Total	**660**	**95,226**	**59.87**

Table A.6. Optimal transportation route and the corresponding transportation cost and health impact for solution D7.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total Trans. Cost ($)**	**Health Impact Full (DALYs)**
Tan Thanh - Thoi Lai - Plant D	88	3,816	0.76
TT Thoi lai - Thoi Lai - Plant D	77	2,114	0.38
X. Thang - Thoi Lai - Plant D	33	1,695	0.35
Dong Hiep - Co Do - Plant D	66	17,298	7.56
Trung Hung - Co Do - Plant D	33	8,745	4.45
NT Co Do - Co Do - Plant D	33	7,647	3.15
Thanh Phu - Co Do - Plant D	33	6,936	2.82
Dong Thang - Co Do - Plant D	33	7,239	2.87
TT P. D - Phong Dien - Plant D	44	10,536	8.56
T. Thoi - Phong Dien - Plant D	22	6,088	5.38
Long Hung - O Mon - Plant D	44	6,884	4.45
Phuoc Thoi - O Mon - Plant D	44	4,880	2.87
Thoi Hoa - O Mon - Plant D	44	5,340	3.11
C. V. Liem - O Mon - Plant D	33	2,766	1.45
Truong Lac - O Mon - Plant D	33	4,848	3.09
Total	**660**	**96,832**	**51.25**

Table A.7. Optimal transportation route and the corresponding transportation cost and health impact for solution C1.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact**
		Trans. Cost ($)	**Full (DALYs)**
TT V. T - Vinh Thanh - Plant C	99	18,738	6.74
Th. Quoi - Vinh Thanh - Plant C	66	13,278	4.98
Th. My - Vinh Thanh - Plant C	33	6,789	2.56
Tan Thanh - Thoi Lai - Plant C	88	16,192	5.78
TT Thoi Lai - Thoi Lai - Plant C	77	12,943	4.38
Xuan Thang - Thoi Lai - Plant C	33	6,336	2.28
Dong Hiep - Co Do - Plant C	66	6,684	1.88
Trung Hung - Co Do - Plant D	33	3,438	1.21
NT Co Do - Co Do - Plant C	33	2,340	0.6
Thanh Phu - Co Do - Plant C	33	1,629	0.41
Dong Thang - Co Do - Plant C	33	1,932	0.47
Thot Not - Thot Not - Plant C	22	4,768	4.5
Thanh Hoa - Thot Not - Plant C	44	10,212	10.16
Total	**660**	**105,279**	**45.95**

Table A.8. Optimal transportation route and the corresponding transportation cost and health impact for solution C2.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact**
		Trans. Cost ($)	**Full (DALYs)**
TT V.T - Vinh Thanh - Plant C	99	18,738	6.74
Th. Quoi - Vinh Thanh - Plant C	66	13,278	4.98
Th. My - Vinh Thanh - Plant C	33	6,789	2.56
Tan Thanh - Thoi Lai - Plant C	88	16,192	5.78
TT T. Lai - Thoi Lai - Plant C	77	12,943	4.38
Xuan Thang - Thoi Lai - Plant C	33	6,336	2.28
Dong Hiep - Co Do - Plant C	66	6,684	1.88
Trung Hung - Co Do - Plant D	33	3,438	1.21
NT Co Do - Co Do - Plant C	33	2,340	0.6
Thanh Phu - Co Do - Plant C	33	1,629	0.41
Dong Thang - Co Do - Plant C	33	1,932	0.47
C. V. Liem - O Mon - Plant C	33	8,661	6.19
Phuoc Thoi - O Mon - Plant C	33	9,555	7.44
Total	**660**	**108,515**	**44.92**

Table A.9. Optimal transportation route and the corresponding transportation cost and health impact for solution C3.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact**
		Trans. Cost ($)	**Full (DALYs)**
TT V. T - Vinh Thanh - Plant C	99	18,738	6.74
Th. Quoi - Vinh Thanh - Plant C	66	13,278	4.98
Th. My - Vinh Thanh - Plant C	33	6,789	2.56
Tan Thanh - Thoi Lai - Plant C	88	16,192	5.78
TT Thoi Lai - Thoi Lai - Plant C	77	12,943	4.38
Xuan Thang - Thoi Lai - Plant C	33	6,336	2.28
Dong Hiep - Co Do - Plant C	66	6,684	1.88
Trung Hung - Co Do - Plant D	33	3,438	1.21
NT Co Do - Co Do - Plant C	33	2,340	0.6
Thanh Phu - Co Do - Plant C	33	1,629	0.41
Dong Thang - Co Do - Plant C	33	1,932	0.47
C. V. Liem - O Mon - Plant C	33	8,661	6.19
Thot Not - Thot Not - Plant C	22	4,768	4.5
Thanh Hoa - Thot Not - Plant C	11	2,553	2.54
Total	**660**	**106,281**	**44.52**

Table A.10. Optimal transportation route and the corresponding transportation cost and health impact for solution C4.

Selected Trans. Route (C. center - Warehouse - Plant)	**Quantity (Tons/month)**	**Total**	**Health Impact**
		Trans. Cost ($)	**Full (DALYs)**
TT V. T - Vinh Thanh - Plant C	99	18,738	6.74
T. Quoi - Vinh Thanh - Plant C	66	13,278	4.98
T. My - Vinh Thanh - Plant C	33	6,789	2.56
Tan Thanh - Thoi Lai - Plant C	88	16,192	5.78
TT T. Lai - Thoi Lai - Plant C	77	12,943	4.38
X. Thang - Thoi Lai - Plant C	33	6,336	2.28
Dong Hiep - Co Do - Plant C	66	6,684	1.88
Trung Hung - Co Do - Plant D	33	3,438	1.21
NT Co Do - Co Do - Plant C	33	2,340	0.6
Thanh Phu - Co Do - Plant C	33	1,629	0.41
Dong Thang - Co Do - Plant C	33	1,932	0.47
C. V. Liem - O Mon - Plant C	33	8,661	6.19
Phuoc Thoi - O Mon - Plant C	11	3,185	2.48
Thot Not - Thot Not - Plant C	22	4,768	4.5
Total	**660**	**106,913**	**44.46**