

Università Ca' Foscari Venezia

Dottorato di ricerca in Analysis and Governance of Sustainable Development, 22° ciclo  
(A. A. 2006/2007 – A.A. 2010/2011)

**IPAT Equation, Life Cycle Inventory Analysis and Dynamic Leontief Model for  
Critical Thinking in Industrial Ecology:  
Decomposition, Attribution and Marginal Analyses for Innovative Solutions**

SETTORE SCIENTIFICO-DISCIPLINARE DI AFFERENZA\*: \_\_\_\_\_

Tesi di dottorato di **Wataru MACHIDA, 955334**

Coordinatore del dottorato  
**prof. Giovanni Maria Zuppi**

Tutore del dottorando  
**prof. Margherita Turvani**

**IPAT Equation, Life Cycle Inventory Analysis  
and Dynamic Leontief Model for Critical  
Thinking in Industrial Ecology:  
Decomposition, Attribution and Marginal  
Analyses for Innovative Solutions**

**Wataru Machida**

# **IPAT Equation, Life Cycle Inventory Analysis and Dynamic Leontief Model for Critical Thinking in Industrial Ecology: Decomposition, Attribution and Marginal Analyses for Innovative Solutions**

## **[Abstract]**

This thesis assists the mission of Industrial Ecology—‘finding innovative solutions to complicated environmental problems’— from the models and analytical techniques point of view. The synthesis part (Chapter 1) clarifies the relation between the models (i.e. IPAT equation, life cycle inventory analysis and dynamic Leontief model) and the analytical techniques (decomposition, attribution and marginal analyses) and sheds light on how they can be utilized for different purposes. Each individual chapter focuses on a theme: comparison between static and dynamic models in the contexts of sustainable consumption and production system and de-growth (Chapter 2), integrated approaches for industrial pollution, especially about data accessibility and elaboration (Chapter 3) and basic indicators, objects and constraints for low-carbon societies (Chapter 4). Depending on the results of the specific cases, the manner in which the models and techniques can be applied is discussed along with limitations in terms of a meta-model for design (Chapter 5).

# **IPAT Equation, Life Cycle Inventory Analysis, e Dynamic Leontief Model per il Pensiero Critico all'Ecologia Industriale: Decomposition, Attribution e Marginal Analyses per le Soluzioni Innovatrici**

## **[Estratto]**

Questa tesi si propone per la missione dell'Ecologia Industriale, di trovare soluzioni innovatrici a problemi ambientali complicati, dall'analisi dei modelli e delle tecniche analitiche. La parte di sintesi (Capitolo 1) chiarisce il rapporto fra i modelli (i.e. IPAT equation, life cycle inventory analysis e dynamic Leontief model) e le tecniche analitiche (decomposition, attribution e marginal analyses) e come possono essere utilizzati per scopi differenti. Ogni capitolo specifico si focalizza su un tema differente: confronto fra i modelli statici e dinamici nei rispettivi contesti del sistema di produzione sostenibile e del consumo e decrescita (Capitolo 2), metodi integrati per gli inquinamenti industriali in particolare per quanto riguarda l'accessibilità e l'elaborazione dei dati (Capitolo 3), e indicatori base, oggetti e vincoli per una società a bassa emissione di carbonio (Capitolo 4). Sulla base dei risultati dei casi specifici, viene sintetizzato sul meta-model per il design, come i modelli e le tecniche possono essere applicati per la missione, e le loro limitazioni vengono inoltre discusse (Capitolo 5).

## Acknowledgement

First, I would like to thank my supervisor, Prof. Margherita Turvani, and the coordinator of the programme, Prof. Giovanni Maria Zuppi, for giving me numerous opportunities and guiding me until the end, especially on rainy days. It is because of them and the support received from the other professors and staff members (especially Ms. Marni Wood) that I was able to spend academically stimulating and enjoyable years in this PhD programme (Analysis and Governance of Sustainable Development (DAGO), organised by the Ca' Foscari University of Venice, the IUAV University in Venice and the School for Advanced Studies in Venice Foundation (SSAV)).

I would also like to thank Prof. Reinout Heijungs from the Leiden University in the Netherlands as he has been always the impetus for and foundation of my work; since I began working on LCA as part of my master's thesis. In his thesis, Prof. Heijungs mentioned, 'I—to speak in Newton's words—stood on the shoulders of giants'. Further, I would like to extend my gratitude to Prof. Masanobu Ishikawa from Kobe University in Japan for consistently providing sharp comments like Zen Osho.

I am indebted to Dr. Pierpaolo Mudu (World Health Organization (WHO), Rome) and Mr. Gaetano Settimo (Italian National Health Institute (ISS), Rome) for collaboratively working on the research on the petrochemical industrial area (Gela, Italy) and for involving me in the *la vita* of Italy.

I have greatly benefited from my association with Prof. Paulo Nunes (FEEM, Venice), Prof. Paolo Santacroce and Prof. Silvio Griguolo (IUAV) for their kindness and support when I was struggling to expand my field of research to biodiversity and sustainable development. I also owe my gratitude to Prof. Anders Strømman and Dr. Troy Hawkins (NTNU, Norway) who opened my eyes to the deep and beautiful forest of modelling.

I am thankful for the support received from Dr. Shuzo Nishioka and Ms. Kyoko Miwa (Institute for Global Environmental Strategies (IGES), Japan) in finalizing my thesis and for teaching me that man does not live by bread alone – that making bread itself is the path towards low-carbon societies (LCS). I would also like to thank Dr. Mikiko Kainuma, Dr. Junichi Fujino (National Institute for Environmental Studies (NIES), Japan) and Prof. Yuzuru Matsuoka (Kyoto University, Japan) who are in the front line of LCS research and has inspired me.

My heartfelt appreciation goes to Dr. Hope (Nozomi) Katagiri, Dr. Kohmei Harada (National Institute for Materials Science (NIMS), Japan) and Prof. Ichiro Daigo (Tokyo University, Japan), for providing innovative ideas on material flows – without them, I may not have been 'recycled'. I would like to convey my gratitude to Mr. Muho Noelke who generously let me experience a microcosm of social people in economic drama on the environmental stage.

Lastly, I would like to thank my family for all their love and encouragement, especially my parents who taught me to appreciate and like science and supported me in all my pursuits.

# Table of Content

## ABSTRACT

## ACKNOWLEDGTEMENT

### CHAPTER 1 [p.6-] **General Introduction: Theme and Meta-Research Questions of the Thesis with Models and Analytical Techniques of Industrial Ecology**

|   |  |         |
|---|--|---------|
| 1 | Introduction   | [p.6-]  |
|   | 1.1 Theme and Scope of the Thesis  |         |
|   | 1.2 Scientific Approach to the Theme   |         |
|   | 1.3 Meta-Question of Each Chapter to the Theme   |         |
| 2 | Three Models and Their Commonalities and Differences in Three Analytical Techniques [p.11-]  |         |
|   | 2.1 The IPAT Equation  |         |
|   | 2.1.1 Decomposition Analysis Applied to the IPAT Equation  |         |
|   | 2.1.2 Attribution Analysis Applied to the IPAT Equation  |         |
|   | 2.1.3 Marginal Analysis Not Applicable to the IPAT Equation  |         |
|   | 2.2 Life Cycle Inventory Analysis (LCI)  |         |
|   | 2.2.1 Decomposition Analysis Applied to LCI  |         |
|   | 2.2.2 Attribution Analysis Applied to LCI  |         |
|   | 2.2.3 Marginal Analysis Applied to LCI   |         |
|   | 2.3 Dynamic Leontief Model and Marginal Analysis   |         |
|   | 2.4 Summary of the Three Models and the Three Analytical Techniques  |         |
| 3 | Problem Definitions and Research Questions for Each Chapter  | [p.24-] |
|   | 3.1 Do Decomposition and Attribution Analyses Explain Cause and Effect for the Future?   |         |
|   | 3.2 Can Attribution Analysis Investigate Data Uncertainty and Supplement a Lack of Data for the Cases Whose Causes Took Place in the Past? |         |
|   | 3.3 How are Objectives and Constraints Established, and What Shall be the Paths (e.g. Speed or Direction)?                                 |         |
| 4 | List of Research Questions   | [p.29-] |
| 5 | References   | [p.31-] |

**CHAPTER 2** **[p.33-]**  
**Static Life Cycle Assessment with External Demand and Dynamic Leontief Model  
with Growth: Two Different Engines in Consumption and Production Systems**

|   |  |         |
|---|--|---------|
| 1 | Introduction   | [p.34-] |
| 2 | Problem Definition and Research Questions                            | [p.35-] |
| 3 | LCI and analogy to IPAT equation                                     | [p.36-] |
| 4 | Dynamic Leontief model and surplus, consumption and growth           | [p.39-] |
| 5 | Conclusion and Discussions on Sustainable Consumption and Production | [p.44-] |
| 6 | References   | [p.48-] |

**CHAPTER 3** **[p.51-]**  
**Industrial Pollution in a Petrochemical Area, Data Accessibility and Elaboration  
from a Public Perspective: a Case Study in Gela, Sicily**

|   |   |         |
|---|---|---------|
| 1 | Introduction  | [p.52-] |
| 2 | The IPPC Directive  | [p.52-] |
|   | 2.1 The European and Italian Pollutant Emission Registers |         |
| 3 | The road to an integrated approach: some questions        | [p.54-] |
| 4 | Public available data: IPPC and Methodologies             | [p.56-] |
| 5 | The case of Gela in Sicily                                | [p.59-] |
|   | 5.1 Emission data quality issues                          |         |
|   | 5.2 Emission, dispersion and monitored concentration data |         |
|   | 5.3 Risk to humans  |         |
| 6 | Discussion  | [p.68-] |
| 7 | Conclusions   | [p.70-] |
| 8 | References  | [p.71-] |

**CHAPTER 4** **[p.75-]**  
**Is Low Carbon Society Embedding or Embedded in Economy? Speed on the  
Constraint or Liberation from it**

|   |   |         |
|---|---|---------|
| 1 | Introduction: What is low-carbon society (LCS) and how to approach this | [p.76-] |
| 2 | Problem definitions and research questions                              | [p.76-] |
|   | 2.1 Problem definition 1: Economy is not everything for LCS             |         |
|   | 2.2 Problem definition 2: Speed on the constraint of liberation from it |         |
|   | 2.3 Research questions  |         |
| 3 | Data and methodologies  | [p.80-] |
| 4 | Arguments and results   | [p.82-] |
|   | 4.1 IPAT equation and basic indicators for LCS                          |         |
|   | 4.2 Framing objects and constraints                                     |         |
|   | 4.3 Historical and future paths toward LCS                              |         |
| 5 | Conclusion and discussion   | [p.90-] |
| 6 | References  | [p.91-] |

**CHAPTER 5** **[p.93-]**  
**General Discussion and Conclusions: Answers to Meta-Research Questions in  
Relation to Meta-Framework**

|   |  |          |
|---|--|----------|
| 1 | Answers to Meta-Research Questions and Discussion        | [p.93-]  |
| 2 | Overall Discussion in Meta-Framework                     | [p.98-]  |
| 3 | List of Answers to Meta- and Specific Research Questions | [p.102-] |
| 4 | References   | [p.106-] |

# CHAPTER 1

## General Introduction:

### Theme and Meta-Research Questions of the Thesis with Models and Analytical Techniques of Industrial Ecology

#### 1. Introduction

This section first states the theme of the thesis and then provides brief overviews of the following sections of the first chapter: a synthesis of Chapters 2-4, problem definitions and meta- and sub-research questions for each chapter.

##### 1.1. Theme and Scope of the Thesis

The mission of industrial ecology is ‘finding innovative solutions to complicated environmental problems’ (ISIE, 2009), which is the theme of this thesis. How people differently perceive problems and solutions results in different approaches with different methodologies.

Environmental problems can be categorized based on whether they address the whole situation at a particular point in time or focus on the relative changes in the situation over time. For instance, one might be concerned about worldwide sulphur dioxide emissions (e.g. 100 tons in the year 2000). Then he might like to attribute the total emissions to each part of the total emissions by each product/activity (e.g. 70 tons by consumption of product X and 30 tons by that of Y). Life cycle assessment (LCA), as explained later, exclusively attributes each part of total emissions to each part of external demand (attribution analysis). In another instance, one could focus on the change in emissions (e.g. sulphur dioxide emissions increased by 51.8 tons between 2000 and 2010). The change could be decomposed into several variables (decomposition analysis: e.g. 13.8 tons by population growth, 18 tons by increases in affluence and 20 tons by changes in technological efficiency).

The difference between attribution and decomposition analyses corresponds to the difference between addition and multiplication. The former example of attribution analysis can be written as follows:

$$100 \text{ tons of total emissions} = 70 \text{ tons from consuming X} + 30 \text{ tons from consuming Y.}$$



Meanwhile, the latter example of decomposition analysis can be written as follows:

$$151.8 \text{ ton} = 100 \text{ ton} \times (110\% \times 115\% \times 120\%).$$

Owing to a 10% population growth, increase in affluence by 15% and decrease in technological efficiency by 20%, total emissions increased from 100 tons to 151.8 tons.

Innovative solutions which can be derived from such analyses have some variations. Suppose that environmental impacts (e.g. health risks) are visible at present because of emissions in the past and environmental actions are required to prevent further impact in the future.

One type of solution is *assigning responsibility*. For example, if the environmental damages can be monetarily converted into 100 million dollars for compensation purposes, 70 million dollars would be assigned to a certain activity and 30 million dollars to the other activity. Attributing responsibility does not necessarily reflect an explanation of cause and effect. Scapegoats can serve a useful purpose in society even when it is obvious that they are not the cause. Meanwhile, scientific approaches try to associate responsibility with cause and effect.

*Giving an explanation for cause and effect* has several merits. When one person allegedly ‘causes’ damage to other people, it can be said that he is responsible to them. Under the logical reasoning of science, it is possible for everyone to share this notion if the assumptions are accepted by all. This merit applies to what has already happened. Another merit is for *taking collective actions in the future*. When the reasoning behind cause and effect is shared, it is easy to reach a consensus to take collective actions though it might also clarify conflicting interests.

What has already happened cannot be changed. Apart from learning from the past and taking appropriate actions in the future, comprehending the past would involve how one can subjectively (emotionally or rationally) accept it because understanding it differently cannot change the past itself but only the meaning assigned to it. On the other hand, analyzing the relationship between causes at present and effects in the future would help to facilitate choosing appropriate actions to reach favourable outcomes. In the logic of the above example, it may be reasonable to expect that 100 tons of emissions could be reduced by 70 tons by eliminating consumption of product X (marginal analysis).

However, a certain type of ‘logic’ as applied to cause and effect does not necessarily lead to expected outcomes even when the logic is consistent and the data used does not contain any defects. Suppose that there is 150 dollars of surplus from a certain economy (e.g. they produce 350 dollars of products and services of which 200 dollars has to be spent as intermediate inputs) and originally this entire surplus is spent on consumption of product X (100 dollars) and product Y (50 dollars). This can be written as follows:

150 dollars of surplus = 100 dollars of X consumption + 50 dollars of Y consumption.

Using one type of logic, when 50 dollars of Y consumption is eliminated from the right-hand side (RHS) of the equation, the surplus would be reduced to 100 dollars. The RHS determines the total size of the economy (*Logic A*). In the other type of logic, the amount of surplus stays the same on the left-hand side (LHS) of the equation and the 50 dollars would be used for investment in economic growth for the future. The LHS is the driver of the economy (*Logic B*). In *Logic B*, the total emissions in the future could be higher than that at present. If so, these two types of logic are not consistent with each other.

*Logic A:*

100 dollars of surplus = 100 dollars of X consumption

*Logic B:*

150 dollars of surplus = 100 dollars of X consumption + 50 dollars of investment for growth

In *Logic A*, when the RHS does not change, the system is in a steady state (i.e. only change creates change). Meanwhile, *Logic B* includes a mechanism for growth which results in dynamic behaviours in a sense that the state at time  $t$  produces changes at time  $t+1$  (i.e. the state itself is the source of change).

When a state comes from a state (e.g. 100 tons of emissions comes from 100 dollars of X consumption and 50 dollars of Y consumption), or when a change comes from a change (e.g. 30 tons of emissions reduction comes from the elimination of 50 dollars of Y consumption), it is within the logic of decomposition and attribution analyses. For instance, it is possible to dissect states (or changes) of consumption and emissions into parts and relate a part of consumption to the corresponding part of emissions.

However, when a change comes from a state as a whole (e.g. total surplus minus total consumption is the degree of growth), the approach of anatomically cutting up causes and effects into pieces does not seem to work because the sum of each sub-system (e.g. each static life-cycle chain) cannot fully explain the dynamic behaviour of the whole system.

The degree of detail in data and data uncertainty is also an issue related to the concept of time and the anatomic approach. If the target for the whole system (e.g. minimizing total greenhouse gas (GHG) emissions) can be broken down into several targets (e.g. minimizing GHG emissions from consumption of food, clothes, etc), then it is worth cutting everything into pieces (e.g. GHG emissions from potatoes, tomatoes, carrots, etc.) and collecting as precise data as possible. And to

achieve the target as a whole, each person could only focus on his own target in a certain sub-system. However, that ‘a target and a system can be divided into sub-systems in which each person has to focus only on his sub-system’ is an assumption.

A person who accepts this assumption would think that his efforts to reduce GHG emissions in his life would surely ‘positively’ contribute to global emissions reductions even though some part of his efforts might be cancelled out by his interaction with others (e.g. the rebound effect). A belief in this logic does not necessarily guarantee corresponding results in reality. In another type of logic based on the dynamic concept of growth, reducing one’s consumption and emissions at present would lead to more growth in the economy for the future and therefore more production and emissions in the future (this mechanism is further discussed with the dynamic Leontief model in Chapter 2). In this dynamic type of logic, the concept of time and the view that a state itself is an origin of a change, which cannot be found in the static anatomic approaches, are crucial.

In addition to the different behaviours of the static and dynamic models, when these types of logic are used, they tend to define objects and constraints so that trade-offs exist and equilibrium points or optimal paths are found in such trade-offs. For instance, it is often assumed that there is a trade-off between gross domestic product (GDP) (object) and GHG emissions (constraint) and if there is a constraint on emissions (e.g. 17 G-ton/year), GDP is maximized when the constraint is always just met (i.e. 17 G-ton/year, not less). Meanwhile, it would also be possible to set the object as ‘free’ from the constraint itself. In this case, the *direction* of green economic growth is targeted rather than the *speed* of GDP growth. For instance, innovative solutions would lie not only in how to structure logic in the energy and material flows of an economic system but also in how to frame objects and constraints in society.

Starting from the theme, all of the above arguments constitute the scope of this thesis.

## 1.2. Scientific Approach to the Theme

For the above-mentioned theme of this thesis, *finding innovative solutions to complicated environmental problems*, a scientific approach is further framed in Section 2 of this chapter.

The arguments for assigning responsibility, explaining causes and effects and their anatomic relationships and foreseeing the consequences of our actions can be covered by comparing three different kinds of analytical techniques: decomposition, attribution and marginal analyses. Decomposition analysis involves decomposing a change in a dependent variable (e.g. emissions) into changes in independent variables (e.g. population, affluence and technology). In attribution analysis a part of the explained variable is attributed to a corresponding part of an explanatory variable (e.g. 20% of the total emissions are explained by food consumption). Marginal analysis involves

estimating the behaviour of the system in the future.

To compare these three analytical techniques, the following three models are reviewed: the IPAT equation, life cycle inventory analysis (LCI) and the dynamic Leontief model. These models are the core methodologies used throughout the chapters of the thesis (LCI and the dynamic Leontief model in Chapter 2, LCI in Chapter 3 and the IPAT equation in Chapter 4). Each chapter is written to suggest and discuss innovative solutions for each case (i.e. sustainable consumption and production, pollution in an industrial area and low-carbon societies) while highlighting the pros and cons of these models and the challenges to overcoming the limitations of these approaches.

Section 2 of this chapter will help readers understand the linkages between the chapters and how this chapter functions as a synthesis for scientifically approaching the theme in an integrative manner (Section 1.1).

### **1.3. Meta-Question of Each Chapter to the Theme**

While each chapter was originally designed to provide concrete innovative solutions to each chapter's complicated environmental problem, the chapters also provide general answers to the following meta-questions which cover a considerable part of the theme. These questions are further discussed in Section 3 of this chapter.

Chapter 2 poses the question: '*Do decomposition and attribution analyses explain causes and effects for the future?*' This question addresses how to foresee the future for making decisions in the present in addition to assigning responsibility and explaining causes and effects using a consistent type of logic (i.e. marginal analysis apart from decomposition and attribution analyses).

The research question of Chapter 3 is: '*Can attribution analysis investigate data uncertainty and supplement a lack of data for the cases whose causes took place in the past?*' Different from marginal analysis which addresses the future, this approach identifies the degree of environmental impact for each production activity observed at present (i.e. attribution analysis) with uncertain and missing data. Assigning responsibility is one of the main purposes of such an analysis. Even when the anatomic approach is necessary and effective, it would not be possible to cut everything into fine pieces and collect precise data for each piece because of limited resources for data gathering. Therefore, it is important to prioritize the parts on which to be focused in more detail.

Chapter 4 asks: '*How are objectives and constraints established, and what shall be the paths (e.g. speed or direction)?*' The theme includes an alternative approach to objects and constraints: setting the object as 'free' from the constraint itself (direction) beyond the trade-off (speed). Starting from the equation for decomposition analysis in the IPAT equation model, the IPAT variables are depicted in phase diagrams so that the direction of the path rather than the speed can be

schematically visualized and emphasized.

The answers to these meta-questions supported by sub-research questions (see Section 3 in this chapter or the corresponding chapters) are discussed throughout these chapters and summarized in the last synthesis chapter.

In the following section, the three analytical techniques (decomposition, attribution and marginal analyses) and the three models (the IPAT equation, LCI and the dynamic Leontief model) are compared to scientifically approach the theme of this thesis.

## 2. Three Models and Their Commonalities and Differences in Three Analytical Techniques

The core methodologies employed in this thesis are the IPAT equation, life cycle inventory analysis (LCI) and the dynamic Leontief model. In this section, the three methodologies are briefly reviewed and their commonalities and differences are discussed together with the three different types of analytical techniques: decomposition, attribution and marginal analyses.

### 2.1. The IPAT Equation

In 1971, Ehrlich & Holden introduced the original form of the IPAT equation,  $I = P \cdot F$ , where  $I$  is environmental impact,  $P$  is population and  $F$  is per capita impact, concluding ‘population control, the redirection of technology, the transition from open to closed resource cycles, the equitable distribution of opportunity and the ingredients of prosperity must all be accomplished if there is to be a future worth having’.

In 1995, Thomas Graedel and Braden Allenby published, *Industrial Ecology*, the first textbook in the field, and industrial ecology has adopted the following IPAT variant as its ‘master equation’ (Chertow, 2000). An example of the definition of each variable is as follows:

$$i = p \times a \times t \quad (1)$$

**where**  $i$  = Emission,  $p$  = Population,  $a = \frac{\text{GDP}}{\text{Population}}$ ,  $t = \frac{\text{Emission}}{\text{GDP}}$ .

$i, p, a$  and  $t$ : scalar

Note that  $i$  is defined as environmental emissions (e.g. SO<sub>2</sub> emissions) rather than environmental impacts (e.g. risk for cancer) here since Life Cycle Inventory Analysis (LCI), which calculates

emissions from external demands, is one of the core methodologies in this thesis while Life Cycle Impact Assessment (LCIA), which evaluates environmental impacts from emissions, is not. LCI and LCIA are two of the four phases of Life Cycle Assessment (LCA) (i.e. Goal and Scope Definition, LCI, LCIA and Interpretation). (See Guinée et al. (2002) for details.)

It is written in the textbook of Graedel and Allenby, ‘Although the master equation should be viewed as conceptual rather than mathematically rigorous, it can be used to suggest goals for technology and society’. And the equation does take on the characteristics of a mathematical identity (Chertow, 2000). For instance, even though the measurement of population, GDP and emissions is not precise, this equation always holds true when the two population and GDP values are cancelled out.

$$\text{Emission} = \cancel{\text{Population}} \times \frac{\cancel{\text{GDP}}}{\cancel{\text{Population}}} \times \frac{\text{Emission}}{\cancel{\text{GDP}}}$$

This characteristic of the identity equation will be a problem for conducting marginal analysis; changing the explanatory variables, population and GDP, does not alter the outcome (i.e. emissions) while independently altering  $p$ ,  $a$  and  $t$  is not possible since they are dependent on each other. By contrast, in LCI each RHS variable in the equation is independent of each other, which contributes to the total emissions on the LHS.

### 2.1.1. Decomposition Analysis Applied to the IPAT Equation

Decomposition analysis applied to the IPAT equation is written as:

$$\begin{aligned} \text{given} \quad & \text{Population}_{t-1} (= p_{t-1}), \text{GDP}_{t-1}, \text{Emission}_{t-1} (= i_{t-1}), \\ & \text{Population}_t (= p_t), \text{GDP}_t \text{ and } \text{Emission}_t (= i_t). \end{aligned}$$

Affluence and technology in time  $t-1$  and  $t$  are defined as follows by eq. (1):

$$\begin{aligned} \text{Affluence}_{t-1} (= a_{t-1}) &= \frac{\text{GDP}_{t-1}}{\text{Population}_{t-1}} \\ \text{Technology}_{t-1} (= t_{t-1}) &= \frac{\text{Emission}_{t-1}}{\text{GDP}_{t-1}} \\ \text{Affluence}_t (= a_t) &= \frac{\text{GDP}_t}{\text{Population}_t} \end{aligned}$$

$$\text{Technology}_t (= t_t) = \frac{\text{Emission}_t}{\text{GDP}_t}.$$

The change in emissions between time  $t-1$  and time  $t$  is decomposed and written as follows:

$$\Delta i = \Delta p \times a_t \times t_t + p_{t-1} \times \Delta a \times t_t + p_{t-1} \times a_{t-1} \times \Delta t \quad (2)$$

where  $\Delta i = i_t - i_{t-1}$ ,  $\Delta p = p_t - p_{t-1}$ ,  $\Delta a = a_t - a_{t-1}$  and  $\Delta t = t_t - t_{t-1}$ .

### 2.1.2. Attribution Analysis Applied to the IPAT Equation

Suppose that there are two types of goods, apples and oranges. Then affluence can be divided as follows:

$$\begin{aligned} \text{GDP}_{total} &= \text{GDP}_{apple} + \text{GDP}_{orange} \\ a_{total} &= \frac{\text{GDP}_{total}}{\text{Population}_{total}} = \frac{\text{GDP}_{apple}}{\text{Population}_{total}} + \frac{\text{GDP}_{orange}}{\text{Population}_{total}} = a_{apple} + a_{orange}. \end{aligned}$$

Thus, the total emissions can be divided into the two parts, each of which is attributed to the corresponding affluence:

$$i_{total} = p_{total} \times (a_{apple} + a_{orange}) \times t_{total} = p_{total} \times a_{apple} \times t_{total} + p_{total} \times a_{orange} \times t_{total} = i_{apple} + i_{orange} \quad (3)$$

### 2.1.3. Marginal Analysis Not Applicable to the IPAT Equation

In contrast to decomposition and attribution analyses, marginal analysis is not applicable to the IPAT equation.

Emissions, population and GDP are first exogenously given, which determines the values of affluence and technology. It is possible to calculate the changes in affluence and technology from the changes in population, GDP and emissions at time  $t-1$  and time  $t$ . However, it is not possible to independently change affluence and technology since these variables depend on each other. Because

of this relationship, the IPAT equation cannot be applied to marginal analysis.

Meanwhile, in LCI, not only decomposition and attribution analyses but also marginal analysis can be applied to investigate the change that is introduced by switching to an alternative (Heijungs, 2001).

## 2.2. Life Cycle Inventory Analysis (LCI)

In 1969, researchers initiated an internal study for The Coca-Cola Company that laid the foundation for the current methods of LCI. In 1991, concerns over the inappropriate use of LCAs to make broad marketing claims made by product manufacturers along with pressure from environmental organizations to standardize LCA methodology led to the development of the LCA standards in the International Standards Organization (ISO) 14000 series (1997 through 2002) (US EPA, 2006). Note that LCA is mathematically equivalent to static input-output analysis (IOA) (Heijungs and Suh, 2002). IOA was first introduced by Wassily Leontief who started to make input-output tables for the US economy in 1931. He announced his plan in the magazine, 'Review Economics and Statistics', in 1936, saying that the input-output tables were an attempt at adjusting the 'General Equilibrium Theory' of L. Walras (1834-1910) to the real national economy, and an attempt at making the 'Tableau Economique' of F. Quesnay (1694-1774) for the US economy (Statistic Bureau of Japan, 2005).

A phase of LCA, LCI is expressed as follows, suggesting some resemblance to the master equation (Heijungs, 2001):

$$\text{environmental intervention} = \text{intervention matrix} \times \text{technology matrix}^{-1} \times \text{external demand}.$$

Technology and intervention matrices in LCI, corresponding to  $t$  in the IPAT equation, are no longer variables depending on emissions and GDP but exogenous variables given by physically measured data. Unlike the IPAT equation, this is not an identity equation in the sense that environmental intervention (i.e. emissions) is calculated by a measured intervention matrix, a technology matrix and external demand and that the calculated environmental intervention is not necessarily identical to the measured one (e.g. directly from a chimney of an industrial plant), which will be further discussed in Chapter 3.

In LCI, when external demand decreases or when technology becomes more efficient, environmental intervention decreases. This behaviour coincides with that of the IPAT equation:  $i$  decreases when  $p$ ,  $a$  and  $t$  also decrease.

The equation for LCI is as follows:



$$\tilde{i}_t = B_t \times \tilde{q}_t$$

**where**

$\tilde{i}_t$  = environmental intervention at time  $t$

$B_t$  = intervention matrix at time  $t$

$\tilde{q}_t$  = total output level of production at time  $t$

$\tilde{i}_t$  and  $\tilde{q}_t$ : vector

$B_t$ : matrix.

Environmental intervention (i.e. emissions) is determined by the total output level of production and the intervention matrix. Production level is determined by external demand and a technology matrix as follows:

$$\tilde{q}_t = T_t^{-1} \times \tilde{f}_t$$

**where**

$$\tilde{f}_t = T_t \times \tilde{q}_t$$

$T_t$  = technology matrix at time  $t$

$\tilde{f}_t$  = external demand at time  $t$

$\tilde{f}_t$ : vector

$T_t$ : matrix.

Thus, emissions are determined by intervention and technology matrices and output level, which is the basis of LCI (eq. 4):

$$\tilde{i}_t = B_t \times T_t^{-1} \times \tilde{f}_t. \quad (4)$$

Intensity matrix,  $\Lambda_t$ , can be defined as follows (Heijungs et al., 2008):

$$\Lambda_t = B_t \times T_t^{-1}.$$

Functional-unit-based LCA which specifies the environmental impact per unit of consumption concentrates on the technology direction, ignoring the other two directions (i.e. population and affluence). However, there are models in which scenarios on future affluence or future population are included and the commodity basket,  $\tilde{f}_t$ , is specified as a function of affluence, population or both as follows (Heijungs et al., 2008):

$$\tilde{f}_t = p_t \times \tilde{a}_t$$

**where**

$p_t$  = population at time  $t$

$\tilde{a}_t$  = affluence (i.e. consumption per person) at time  $t$

$p_t$  : scalar

$\tilde{a}_t$  : vector.

By integrating technology and intervention matrices into an intensity matrix and dividing external demand into population and affluence, the similarities of the variables between the IPAT equation and LCI is evident as shown in Table 1.

**Table 1. Similarities of Variables between IPAT equation and LCI.**

|            | IPAT equation                              | Life Cycle Inventory Analysis   |
|------------|--|---|
| Equation   | $i = p \times a \times t$                  | $\tilde{i}_t = B_t \times T_t^{-1} \times \tilde{f}_t$<br>$= \Lambda_t \times p_t \times \tilde{a}_t$ |
| Impact     | $i$ = Emission                             | $\tilde{i}_t$ : vector  |
| Population | $p$ = Population                           | $p_t$ : scalar  |
| Affluence  | $a = \frac{\text{GDP}}{\text{Population}}$ | $\tilde{a}_t$ : vector  |
| Technology | $t = \frac{\text{Emission}}{\text{GDP}}$   | $\Lambda_t$ : matrix  |

Chertow (2000) stated that industrial ecology views recognize ‘increases in population and affluence can, in many cases, be balanced by improvements to the environment offered by technological systems’. In addition to the focus on technology, the interaction between population and affluence is also worth considering further though this issue is not fully covered in this thesis. Population decreases are foreseen in industrialized countries, and population decreases and the possibility for increases in affluence should be considered together with relatively decreasing labour inputs as capital in a production system as well as monetary debts such as pension systems which possibly had been designed with an assumption of continuous population growth. According to Ayer (2008), ‘without economic growth the tax revenues will not grow fast enough to satisfy the demand for pensions and health services’, ‘the fraction of non-working hours as compared to working hours, increases rapidly as birth-rates decline and life expectancy increases’ and ‘[f]or this reason alone, governments of the richer democracies are addicted to growth’.

In contrast to the IPAT equation, marginal analysis as well as decomposition and attribution analyses are applicable to LCI as shown below.

### 2.2.1. Decomposition Analysis Applied to LCI

In decomposition analysis, the analysis of changes in emissions between the two time periods (e.g.  $t-1$  and  $t$ ),  $\Delta \tilde{i}$ , is decomposed into the parts which consist of the changes in the exogenous variables,  $\Delta B$ ,  $\Delta T^{-1}$  and  $\Delta \tilde{f}$ :

given  $B_{t-1}$ ,  $T_{t-1}$ ,  $\tilde{f}_{t-1}$ ,  $B_t$ ,  $T_t$  and  $\tilde{f}_t$ .

Emissions in time  $t-1$  and time  $t$  are calculated from Eq. (4):

$$\tilde{i}_{t-1} = B_{t-1} \times T_{t-1}^{-1} \times \tilde{f}_{t-1}$$

$$\tilde{i}_t = B_t \times T_t^{-1} \times \tilde{f}_t,$$

Thus, the change in emissions between time  $t-1$  and time  $t$  is decomposed into the three parts as follows:

$$\Delta \tilde{i} = \Delta B \times T_t^{-1} \times \tilde{f}_t + B_{t-1} \times \Delta T^{-1} \times \tilde{f}_t + B_{t-1} \times T_{t-1}^{-1} \times \Delta \tilde{f} \quad (5)$$

where  $\Delta \tilde{i} = \tilde{i}_t - \tilde{i}_{t-1}$ ,  $\Delta B = B_t - B_{t-1}$ ,  $\Delta T^{-1} = T_t^{-1} - T_{t-1}^{-1}$  and  $\Delta \tilde{f} = \tilde{f}_t - \tilde{f}_{t-1}$ .

In eq. (5), the changes in the variables on the RHS,  $\Delta B$ ,  $\Delta T^{-1}$  and  $\Delta \tilde{f}$ , could be interpreted as the causes of the changes in emissions,  $\Delta \tilde{i}$ .

## 2.2.2. Attribution Analysis Applied to LCI

Attribution analysis is the method of dividing total emissions into several parts, each of which is attributed to a corresponding external demand. Each of these can then be interpreted as a cause of the emissions.

Note that it is not always necessary for a person to be reminded of how the part on which he focuses is related to the total. For instance, when conducting LCI on Coca-Cola, informing a person about the life cycle environmental emissions from consuming one bottle of Coke may be effective. Or knowing the impact of his annual consumption of Coke (e.g. 200 bottles) compared to his total food consumption or to all of his consumption activities (i.e. housing, clothing, etc.) may be effective. For this purpose, the use of input-output tables enables one to deal with the total emissions in an economy while calculating the life cycle impact of the part. Hybrid LCA is a methodology that combines input-output tables and LCI (see Hijungs et al., 2002 for details of Hybrid LCA).

Below, total demand,  $\tilde{f}_{total}$ , is divided into a part and the rest,  $\tilde{f}_{part}$  and  $\tilde{f}_{rest}$ .

Examples of relationships between the total and the part can vary: a country/a person, a country/a product, a person/a product or a product/a product part (e.g. a car/ its engine).

Attribution analysis in LCI can be defined as follows:

$$\mathbf{given} \quad \tilde{f}_{total} \quad \text{and} \quad \tilde{f}_{part}.$$

The total emissions,  $\tilde{i}_{total}$ , are divided into the two parts: the emissions attributed to the part,  $\tilde{i}_{part}$ ,

and the rest which is proved to be equal to  $\tilde{i}_{rest}$

$$\tilde{i}_{total} = BT^{-1}(\tilde{f}_{part} + \tilde{f}_{rest}) = \tilde{i}_{part} + \tilde{i}_{rest} \quad (6)$$

$$\mathbf{where} \quad \tilde{f}_{rest} = \tilde{f}_{total} - \tilde{f}_{part}$$

$$\tilde{i}_{total} = BT^{-1}\tilde{f}_{total}, \quad \tilde{i}_{part} = BT^{-1}\tilde{f}_{part} \quad \text{and} \quad \tilde{i}_{rest} = BT^{-1}\tilde{f}_{rest}$$

### 2.2.3. Marginal Analysis Applied to LCI

Marginal analysis by LCI shows the degree to which the changes in exogenous variables at time  $t$  affect emission at time  $t+1$ :

$$\mathbf{given} \quad B_t, \quad T_t, \quad \tilde{f}_t, \quad \Delta B, \quad \Delta T^{-1} \quad \text{and} \quad \Delta \tilde{f}.$$

Emissions at time  $t+1$  can be written as explanatory variables at time  $t$  plus their changes:

$$\tilde{i}_{t+1} = B_{t+1} T_{t+1}^{-1} \tilde{f}_{t+1} = (B_t + \Delta B)(T_t^{-1} + \Delta T^{-1})(\tilde{f}_t + \Delta \tilde{f}) \quad (7)$$

where  $B_{t+1} = B_t + \Delta B$ ,  $T_{t+1}^{-1} = T_t^{-1} + \Delta T^{-1}$  and  $\tilde{f}_{t+1} = \tilde{f}_t + \Delta \tilde{f}$ .

The difference between marginal analysis and decomposition analysis (eq. (7) and (5), respectively) is that the former exogenously gives changes in variables (i.e.  $\Delta B$ ,  $\Delta T^{-1}$  and  $\Delta \tilde{f}$ ) which result in changes in emissions; it calculates changes in emissions at time  $t+1$  between the situations with/without the changes in the variables. Meanwhile, the latter first gives the values of the independent variables at time  $t+1$  and time  $t$ , calculates those of the dependent variables, defines the changes in the variables, and then decomposes the changes in emission variables into the changes in other variables. This difference might be subtle in LCI, a static model, but it is more vivid in a dynamic model such as the dynamic Leontief model since such decomposition procedures cannot be applied to it.

### 2.3. Dynamic Leontief Model and Marginal Analysis

In 1953, Wassily Leontief published a dynamic version of his input-output model (Fleissner, 1990), which is an open dynamic model in a sense that consumption is exogenously given. Meanwhile, Neumann (1945) introduced a closed dynamic model, which has mathematical and theoretical similarities with that of Leontief and unique Eigen-values of a technology matrix interpreted as growth and interest rates (Inoue, 2001) though this is out of the scope of this paper.

As defined in the details of Chapter 2, the dynamic Leontief model can be written as follows:

$$\tilde{q}_{t+1} = C^{-1}((T_{out} - T_{in} + C)\tilde{q}_t - \tilde{f}) \quad (8)$$

where

$\tilde{q}_t$  = total output vector at time  $t$

$C$  = capital matrix

$T_{in}$  = input technology matrix

$T_{out}$  = output technology matrix

$\tilde{f}$  = external demand

$\tilde{q}_t$  and  $\tilde{f}$  : vector

$C$ ,  $T_{in}$  and  $T_{out}$  : matrix.

The total output vector at time  $t+1$  is a function of the same vector at time  $t$ . Part of a ‘surplus’ of the economy allocated to a purpose other than consumption,  $(T_{out} - T_{in})\tilde{q}_t - \tilde{f}$ , is the driving force which determines the behaviours of the model, especially for sustainable consumption and production (see Chapter 2 for details). For discussion on ‘de-growth’ (i.e. producing and consuming less; see Huppel et al. (2009) for further arguments), a question could be posed: Is it possible to reduce consumption and production at the same time in any dynamic logic? One way to answer this question would be to discuss the possibilities of using a surplus for purposes other than for investment into economic capitals. For instance, part of a surplus could be utilized for environmental systems rather than unnecessary consumption and excessive capital formation in production systems, which can be related to the arguments on weak and strong sustainability (see Ayer et al., 1998 for instance). It is also unlikely that ‘the neoclassical growth or general equilibrium models used by energy economists have much to contribute to sustainable consumption research’ (Hertwich, 2005).

Marginal analysis can be conducted by changing variables on the RHS of the equation. For instance, the change in the total output vector at time  $t$  induced by the change in external demand is calculated as follows:

**given**  $\Delta\tilde{f}$

$$\Delta\tilde{q}_f = -C^{-1}\Delta\tilde{f} \quad (9)$$

**where**  $\tilde{q}_{(t+1), with \Delta f} = C^{-1}((T_{out} - T_{in} + C)\tilde{q}_{(t)} - (\tilde{f} + \Delta\tilde{f}))$  and  $\Delta\tilde{q}_f = \tilde{q}_{(t+1), with \Delta f} - \tilde{q}_{(t+1)}$ .

Note that this marginal analysis is a comparison between the two cases (i.e.  $\tilde{q}_{(t+1), with \Delta f}$  and  $\tilde{q}_{(t+1)}$ ) in the same period (i.e. time  $t+1$ ) and not that between time  $t$  and time  $t+1$ . The two different types of comparisons have to be clearly distinguished in the dynamic Leontief model though they are often mixed and do not cause serious problems in static LCI.

To compare with the decomposition analysis of LCI, the change in the total output vector

between time  $t$  and  $t+1$ ,  $\Delta\tilde{q}_{time}$ , is written as follows:

$$\Delta\tilde{q}_{time} = \tilde{q}_{(t+1)} - \tilde{q}_{(t)} = C^{-1}(T_{out}\tilde{q}_{(t)} - T_{in}\tilde{q}_{(t)} - \tilde{f}). \quad (10)$$

Eq. 10 means that the change in total output between time  $t+1$  and time  $t$  comes from the total output at time  $t$ , even when the other exogenous variables (i.e.  $C$ ,  $T_{in}$ ,  $T_{out}$  and  $\tilde{f}$ ) are fixed (see the statement in Section 1.1: ‘state itself is the source of change’). In static LCI, by conducting decomposition analysis, the change in the dependent variable,  $\Delta\tilde{i}$ , is decomposed by changes in the independent variables (see eq. 5); if these exogenous variables are fixed, there is no change in emissions (‘only change creates change’). In the dynamic model, the driving force of changes in output lies in its own state of production and consumption. This is why decomposition analysis cannot be applied to the dynamic model and also why the change between  $t+1$  and  $t$ ,  $\Delta\tilde{q}_{time}$  in eq. 10 and that between the same period,  $\Delta\tilde{q}_f$  in eq. 9, are about two different concepts while equations of decomposition and marginal analyses seem similar in LCI (see eq. 5 and 7). As discussed in the following section, the shift from decomposition analysis to marginal analysis, the ‘reverse’, is clear in the dynamic Leontief model but not in LCI.

The situation is similar in attribution analysis. In static LCI, any part of the production level is attributed to a certain part of the external demand (‘a state comes from a state’). However, the dynamic Leontief model cannot allow such attribution; as seen in eq. (8), the total output vector at time  $t+1$  is a function of not only external demand but also the total output vector at time  $t$  itself.

## 2.4. Summary of the Three Models and the Three Analytical Techniques

The IPAT equation, LCI and the dynamic Leontief model are in the same family of methodologies, which are often employed in industrial ecology. The methodologies themselves are just concepts made of mathematical logic. Whether they could properly analyze and govern a real phenomenon is another issue to be considered. Thus, the limitations of the methodologies shall be critically considered.

Chertow (2000) stated ‘Although the IPAT equation was once used to determine which single variable was the most damaging to the environment, an industrial ecology view reverses this usage, recognizing that increases in population and affluence can, in many cases, be balanced by



improvements to the environment offered by technological systems’.

This reverse of views from merely analysis for observation (i.e. decomposition and attribution analyses) into a proposition of solutions (i.e. marginal analysis) is the origin of the problems discussed in Section 3 in this chapter. It also demonstrates the constructive challenges that these methodologies would face to derive innovative solutions.

One of these challenges is sharply depicted in Chapter 2 for instance. In marginal analysis of static LCI and its extension to the dynamic model (i.e. the dynamic Leontief model), each of these types of logic leads to a different outcome. In static LCI less consumption leads to less environmental intervention while in the dynamic mechanism less consumption would lead to more growth and environmental intervention in the future.

The shift from decomposition analysis to marginal analysis is exactly where the ‘reverse’ came into being and where the logic of static LCI and the dynamic Leontief model results in different outcomes. It can be said that static LCI manages to establish logically consistent decomposition and attribution by eliminating the concept of time, thereby making the model static. Meanwhile, in the dynamic Leontief model, changes in emissions at time  $t$  shall also be decomposed not only into variables at the same time period but also into those at times  $t-1$ ,  $t-2$ ,  $t-3$ ...1 and 0. However, it is not possible to mathematically formulate such a decomposition analysis. It is also not possible to mathematically formulate equations for attribution so that a part of emissions at time  $t$  shall be attributed not only to a part of consumption at time  $t$  but also to parts of consumption at times  $t-1$ ,  $t-2$ , ... 1 and 0. Some might say that ‘change’ and ‘consumption’ taking place at time  $0$  are the original causes to all the effects at time  $t$  since time  $< 0$  does not exist by definition. However, this is not the purpose of the analyses since they are meant to decompose/attribute emissions into each isolated component with ‘visible’ anatomical hands.

The applicability of decomposition, attribution and marginal analyses to the IPAT equation, static LCI and the dynamic Leontief model are summarized in Table 2.

**Table 2. Applicability of the three analyses to the three models.**

|                        | <i>Decomposition<br/>Analysis</i> | <i>Attribution<br/>Analysis</i> | <i>Marginal<br/>Analysis</i> |
|------------------------|-----------------------------------|---------------------------------|------------------------------|
| IPAT equation          | +                                 | +                               | -                            |
| (Static) LCI           | +                                 | +                               | +*                           |
| Dynamic Leontief Model | -                                 | -                               | +*                           |

\*Note: The behavioural trends between LCI and the dynamic Leontief model are different.

These three models and the three analytical techniques are the methodologies and the concepts used in Chapters 2-4 and the meta-research questions posed for each chapter are positioned on the

methodological bases that predecessors of this field have founded.

In the next section, problem definitions, meta/specific-research questions and a brief explanation of each chapter will be shown.

### 3. Problem Definitions and Research Questions for Each Chapter

In Section 1, the theme of the thesis is stated: the mission of industrial ecology is ‘finding innovative solutions to complicated environmental problems’ (ISIE, 2009).

In Section 2, scientific approaches to the theme are discussed with the three models and the three analytical techniques, all of which are important and useful methodologies in the industrial ecology field. Through the comparison as seen in Table 2, their limitations (thus problems and challenges to be overcome) are also identified, which could be summarized as ‘[a]lthough the IPAT equation was once *used to determine* which single variable was the most damaging to the environment, an industrial ecology view *reverses* this usage, recognizing that *increases in population and affluence* can, in many cases, be *balanced by improvements to the environment offered by technological systems*’ (Chertow, 2000).

Regarding the ‘reverse’, the IPAT equation was once used only for decomposition and attribution analyses. Unlike the IPAT ‘identity’ equation, LCI has expanded its coverage further to marginal analysis: all of the decomposition, attribution and marginal analyses can be applied to LCI under its consistent logic as derivations from the one equation (i.e. eq. 5, 6 and 7 derived from eq. 4). However, the consistency of logic does not necessarily guarantee that logic is always more proper than other approaches for finding innovative solutions. To identify the problems (e.g. static and dynamic models behave differently in marginal analysis) and overcome them, a question is posed: ‘*Do decomposition and attribution analyses explain causes and effects for the future?*’ (Section 3.1 and Chapter 2).

The IPAT equation and LCI can be ‘*used to determine*’ the most damaging variables through decomposition and attribution analyses. Unlike marginal analysis, one of the main characteristics of these analyses is to identify the causes of emissions. For instance, attribution analysis can be used to assign responsibility. Especially when conducting the analysis in higher resolution, uncertain and missing data would be the problems taken into consideration. The meta-research question for Chapter 3 is: ‘*Can attribution analysis investigate data uncertainty and supplement a lack of data for the cases whose causes took place in the past?*’ (also see Section 3.2).

‘*[I]ncreases in population and affluence*’ lead to increases in GDP and emissions which can be ‘*balanced by improvements to the environment offered by technological systems*’. This way of thinking would be based on the assumption that trade-offs exists between GDP growth and emission

reduction. Models to maximize objects (e.g. GDP) while satisfying constraints (e.g. emissions) are also based on the existence of such trade-offs. However, maximizing GDP or speed of GDP growth is only one way to define an object. An alternative can be the direction of green growth. Thus, Chapter 4 asks: ‘*How are objectives and constraints established, and what shall be the paths (e.g. speed or direction)?*’(also see Section 3.3).

The answers to these meta-questions, supplemented by the sub-research questions, are sought in Chapters 2-4 and summarized in the last synthesis chapter.

### 3.1. Do Decomposition and Attribution Analyses Explain Cause and Effect for the Future?

Decomposition analysis can calculate the contribution of each variable to a change in emissions. As seen in Table 2, the analysis can be applied to both the IPAT equation (see eq. 2) and static LCI (see eq. 5); a change in emissions is exclusively dissected into changes in population, affluence and technology, for instance.

Attribution analysis can break down total emissions into each emission part which exclusively corresponds to each part of the ‘alleged’ causes. In static LCI, by assuming that all the emissions are caused by external demand, given that other exogenous variables are fixed, attribution analysis can be applied to the equations. Total emissions can be divided into each part which is attributed to each part of the final demand vector in LCI (see eq. 6) or affluence scalar in the IPAT equation (see eq. 3).

These two types of analyses are observations in a sense in that they do not originally include an intention to change any variables for solving problems (e.g. emission reduction) as marginal analysis does. Also, they are mathematically consistent in one-to-one-mapping between the two sets of variables (i.e. three different parts of  $\Delta\tilde{i}$  and  $[\Delta B, \Delta T, \Delta\tilde{f}]$  for decomposition analysis and  $[\tilde{i}_{part}, \tilde{i}_{rest}]$  and  $[\tilde{f}_{part}, \tilde{f}_{rest}]$  for attribution analysis in the case of LCI). Meanwhile, a cause and effect relationship implies more than observation. It is expected that if one part of a cause disappears, the corresponding effect also disappears. For instance, in decomposition analysis, if a change in technology does not take place (i.e.  $\Delta T^{-1} = 0$ ), the corresponding change in emissions also would vanish (i.e.  $B_{t-1} \times \Delta T^{-1} \times \tilde{f}_t = 0$ ) (see eq. 5). In attribution analysis, if one part of a final demand would be prevented (e.g.  $\tilde{f}_{part} = 0$ ), the corresponding part of emissions can

be reduced (i.e.  $\tilde{i}_{part} = 0$ ) (see eq. 6).

However, such a cause-effect explanation in decomposition and attribution analyses has been criticized for the existence of the rebound effect. For instance, if consumption of gelato (i.e.  $\tilde{f}_{part}$ ) is prevented, consumption of cars (i.e.  $\tilde{f}_{rest}$ ) will increase. This rebound effect can be calculated in computational general equilibrium (CGE) by introducing non-linear production and utility functions. Note that this thesis does not thoroughly discuss rebound effects (see UKERC (2007) for its detailed classifications, for instance). In addition to the concept of the rebound effect, this thesis gives a critical view of static cause-effect relationships.

Apart from the rebound effect which can be calculated with a static model, Chapter 2 focuses on the differences between decomposition and marginal analyses. In LCI, the difference between them (see eq. 5 and 7) is subtle. Meanwhile, decomposition analysis cannot be applied to the dynamic Leontief model. Furthermore, the logic used to explain the change in output between two different time periods (see  $\Delta\tilde{q}_{time}$  in eq. 10) is different than in marginal analysis (to compare between the situations with/without  $\Delta\tilde{f}$  both at time  $t$  and time  $t+1$  see  $\Delta\tilde{q}_f$  in eq. 9).

By comparing the static and dynamic models, it can be said that it is useful to conduct decomposition and attribution analyses with LCI to deal with ‘responsibility’ for the past, but there is an issue of what are the real ‘causes and effects’. In attribution analysis of the past, it could be assumed that a measurable responsibility for total emissions (e.g. 100) exists. This responsibility can be quantitatively attributed to a part of final demand (e.g. 30 for  $\tilde{f}_{part}$ , 70 for  $\tilde{f}_{rest}$ ) and the change in this responsibility (e.g. 100 to 110) can be decomposed into exogenous variables (e.g. 3 by  $\Delta B$ , 4 by  $\Delta T^{-1}$  and 3 by  $\Delta\tilde{f}$ ). Meanwhile, for actions and governance for the future, cause-effect relationships would be more important than attribution and decomposition of responsibilities though mathematical differences between them are subtle in LCI. Thus, the following meta-research question is set, supported by specific research questions (see Research Questions 1.1-1.4 in Section 4) in Chapter. 2.

*Research Question 1:* Do decomposition and attribution analyses explain cause and effect for the future?

### **3.2. Can Attribution Analysis Investigate Data Uncertainty and Supplement a Lack of Data for the Case Whose Causes Took Place in the Past?**

When static LCI is used to foresee the future of a system, the main challenges concern logic on how a system behaves. Such challenges include the fact that rebound effects which are not considered in marginal analysis of LCI might occur and that the dynamic logic of a system's behaviour regarding allocation of a surplus between consumption and investment is not embedded in LCI, which will be further discussed in Chapter 2.

However, such logic on how a system behaves might not be a serious challenge to analyzing past phenomena. The past has already occurred and the state is uniquely fixed regardless of logic (i.e. the past cannot be changed) though there could be a debate regarding interpretations of what happened and why it happened.

Clarifying what and why would help to assign responsibility (e.g. 100 tons of GHG are emitted of which 15 tons are attributed to a certain activity). For instance, compensation could be based on such attributed responsibility. If the assumption of the logic is shared among stakeholders, LCI could give consistent answers to such situations.

However, even though the logic is robust, lack and uncertainty of data would be a great challenge. In Chapter 3, it is ascertained whether data is properly registered and monitored and whether attribution analysis can explain the health impact observed at present. Attribution analysis could be employed to investigate data uncertainty and to supplement a lack of data by using a general database of technology processes. The following meta-question is set with specific ones (see Research Questions 2.1-2.3 in Section 4).

*Research Question 2:* Can attribution analyses investigate data uncertainty and supplement a lack of data for the case whose causes took place in the past?

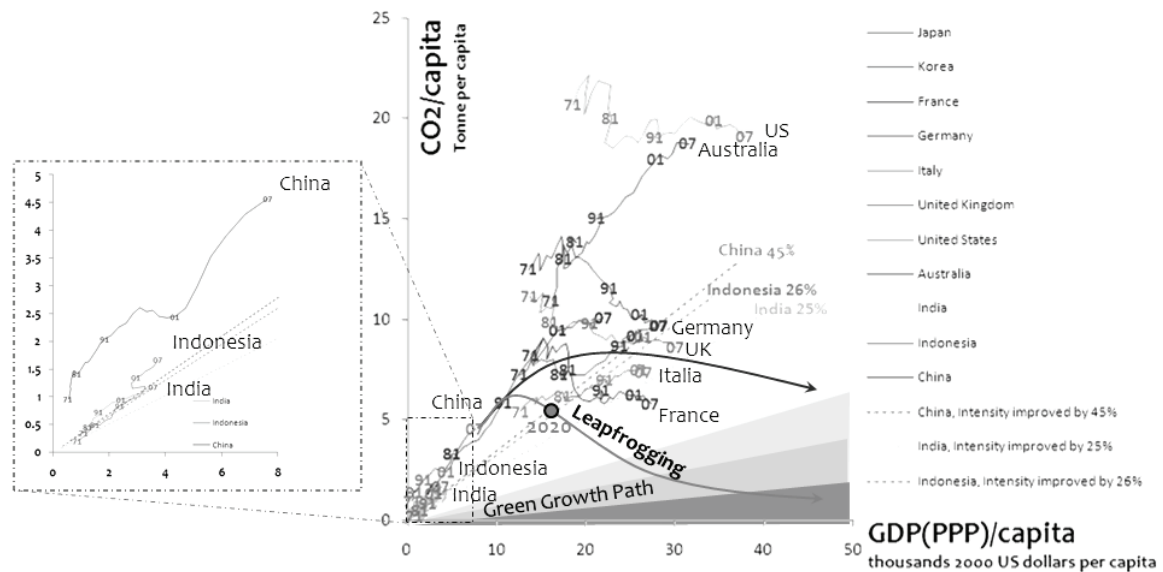
### **3.3. How are Objects and Constraints Established and What Shall be the Paths (e.g. Speed or Direction)?**

To derive innovative solutions to address the threat of climate change and to achieve the development of societies, the concept of a low-carbon society (LCS) has been proposed. A LCS: 1) takes actions that are compatible with the principle of sustainable development, ensuring that the development needs of all groups within society are met; 2) makes an equitable contribution toward the global efforts to stabilize atmospheric concentrations of carbon dioxide and other GHGs at a

level that will avoid dangerous climate change through deep cuts in global emissions; 3) demonstrates high levels of energy efficiency and uses low-carbon energy sources and production technologies; and 4) adopts patterns of consumption and behaviour that are consistent with low levels of GHG emissions (definition from NIES (2006)).

To quantitatively analyze and propose options to achieve a LCS, the goal shall be to interpreted into measurable indicators of objects and constraints. In Chapter. 4, the three different kinds of objects (i.e. total GDP, GDP per capita and a social indicator) and the two constraints (i.e. total emissions and emissions per capita) are considered. In addition to whether the objects are realized and the constraints are satisfied or not, a considerable amount of attention is paid to whether a path gives priority to the speed it takes to maximize the objects or to the directions which liberate the path from the constraints.

For instance, Figure 1 shows the growth paths of G20 countries for the period 1971–2007 on the phase diagram of GDP per capita and CO<sub>2</sub> emissions per capita. Supposing that GDP per capita is the object and CO<sub>2</sub> emissions per capita is the constraint, the phase diagram does not schematically show the speed in a direct manner (i.e. how quickly GDP per capita is growing) but the direction expressed in slope (i.e. how green the path is<sup>1</sup>).



**Figure 1. Direction of Growth: Green Growth and Leapfrogging<sup>2</sup>.**

In models such as the IPAT equation, LCI and the dynamic Leontief model, the variables are interrelated in mathematical equations as shown in eq. 1, 4 and 8, which show certain aspects of

<sup>1</sup> Green Growth is defined as a path of economic growth in which emission intensity (i.e. GHG emission per GDP) is small and GHG emission per capita is not growing as rapidly as affluence (GDP per capita).

<sup>2</sup> Constructed from IEA data (2009).

economic system behaviours. However, deciding which variables shall be objects and constraints and their implication for desirable paths (e.g. priority to speed or direction) is another issue to be considered, and the following meta-question is set with specific ones (see Research Questions 3.1 and 3.2), which will be further discussed in Chapter 4.

the following question is posed:

*Research Question 3:* How are objectives and constraints established and what shall be the paths (e.g. speed or direction)?

## 4. List of Research Questions

The theme of the thesis is stated, how to scientifically approach the theme with the three models and the three analytical techniques is discussed, and the meta-research questions based on the approach are formulated in the above sections.

In the following chapters, these meta-research questions are discussed for each case with each set of specific questions. The title of each chapter and the list of meta-questions and specific research questions are given below.

### Chapter 2:

Static Life Cycle Assessment with external demand and Dynamic Leontief Model with growth:

Two Different Engines in Consumption and Production Systems

*Research Question 1* Do decomposition and attribution analyses explain cause and effect for the future?

*Research Question 1.1.* Is the ‘reverse’ indicated in Chertow (2000) identified between the equations of decomposition and marginal analyses in LCI?

*Research Question 1.2.* Does technology with efficient use of energy and materials lead to less environmental impacts or contrarily more?

*Research Question 1.3.* Does less consumption leads to less environmental impacts or contrarily more?

*Research Question 1.4.* How can the different behaviours between the static and dynamic models be interpreted?

### **Chapter 3:**

Industrial Pollution in a Petrochemical Area, Data Accessibility and Elaboration from a Public Perspective: a case study in Gela, Sicily

*Research Question 2* Can attribution analyses investigate data uncertainty and supplement a lack of data for the cases whose causes took place in the past?

*Research Question 2.1.* Which scopes (e.g. time, place, chemicals, stage) shall be taken into account?

*Research Question 2.2.* Are registered emissions and calculated emissions from production data consistent [uncertainty of data]? Can the calculated ones supplement lack of data?

*Research Question 2.3.* Are monitored emission concentrations in the air and calculated concentrations from emission data consistent [uncertainty of data]? Can the calculated ones supplement lack of data?

### **Chapter 4:**

Is low carbon society embedding or embedded in economy?:  
Speed on the constraint or liberation from it

*Research Question 3.* How are objectives and constraints established, and what shall be the paths (e.g. speed or direction)?

*Research Question 3.1.* Starting from the IPAT equation, what are the basic indicators, objectives, and constraints to shape the arguments of LCSs?

- Whether the object of LCS is GDP or GDP/capita?
- Whether the main object of LCS can be measured by economic indicators such as GDP and GDP/capita?



- Research Question 3.2.* What are the historical paths of several countries and what can be said for their future paths toward LCSs?
- Whether the path gives priority to the speed to maximize the objects or to the directions which liberate their paths from the constraints?

## 5. References

- Ayer, R. U., J. C. J. M. van den Bergh and J. M. Gowdy. 1998. Viewpoint: Weak Versus Strong Sustainability, Tinbergen Institute Discussion Papers, number 98-103/3.
- Ayer, R. U. 2008. Sustainability economics: Where do we stand?, *Ecological Economics*, 67, 281-310.
- Chertow, R. M. 2000. The IPAT Equation and Its Variants: Changing Views of Technology and Environmental Impact, *Journal of Industrial Ecology*, 4(4): 13-29.
- Ehrlich, P. and J. Holden. 1971. Impact of population growth, *Science*, 171, 1212-17.
- Fleissner, P. 1990. Dynamic Leontief Models on the Test Bed, *Structural Change and Economic Dynamics*, 1(2): 321-357.
- Graedel, T. and B. Allenby. 1995. *Industrial ecology*. Englewood Cliffs, NJ: Prentice Hall.
- Guinée, J.B., M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. Koning, L. Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, H. Bruijn, R. Duin, M.A.J. Huijbregts. 2002. *Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. Iia: Guide. Iib: Operational annex. III: Scientific background*. Kluwer Academic Publishers.
- Heijungs, R. 2001. *A theory of the Environment and Economic Systems: a unified framework for ecological economic analysis and decision-support*, Edward Elgar Publishing, Inc.
- Heijungs, R. and S. Suh. 2002. *The computational structure of life cycle assessment*, Kluwer Academic Publishers.

Heijungs, R., G. Huppes and J. Guinée. 2008. *A Scientific Framework for LCA*, Deliverable D15 of the CALCAS project.

Hertwich, E.G. 2005. Consumption and the Rebound Effect: An Industrial Ecology Perspective, *Journal of Industrial Ecology*, 9(1-2): 85-98.

IEA. 2009. *CO2 Emissions from Fuel Combustion – Highlights*.

Inoue, H. 2001. *Linear Economics*, Tokyo, Hakutoh (in Japanese).

ISIE, 2009. Web page of International Society for Industrial Ecology.  
<http://www.is4ie.org/history> (accessed on 07/04/2009)

Neumann, J.V. 1945. A Model of General Economic Equilibrium, *The Review of Economic Studies*, 13(1):1-9.

NIES. 2006. *Developing Visions for a Low-Carbon Society (LCS) through Sustainable Development*, Executive Summary, National Institute for Environmental Studies, Tsukuba.

Statistics Bureau of Japan (2009) 2005 Input-Output Tables for Japan - Explanatory Notes –  
<http://www.stat.go.jp/english/data/io/io05.htm> (accessed on 12/12/2010)

UKERC. 2007. *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*, UK Energy Research Centre.

US EPA 2006. *Life Cycle Assessment: Principles and Practice*, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, EPA/600/R-06/060.

## CHAPTER 2

### Static Life Cycle Inventory Analysis with External Demand and Dynamic Leontief Model with Growth:

#### Two Different Engines in Consumption and Production Systems

##### Abstract

The static models of industrial ecology, the IPAT equation and life cycle inventory analysis (LCI), are contrasted with the dynamic Leontief model, and the applicability of and difference between decomposition and marginal analyses are discussed. Less consumption and more efficient technology lead to low emissions in LCI, although, contrarily, they will also spur greater economic growth and hence greater production and emissions in the future. In the static LCI model, energy and material flows are driven by external demand, that is, the consumption system. By contrast, in the dynamic Leontief model, the economic engine is the production system. From these theoretical considerations and in light of the literature on sustainable consumption and production (SCP), we address the question of de-growth—*Is it possible to reduce consumption and production at the same time?* The focus is on the *social* meaning of economic activity, since people constitute both consumers and producers.

##### Keywords

Life cycle inventory analysis; dynamic Leontief model; Input-output analysis; sustainable consumption and production; de-growth; IPAT equation; growth; surplus; industrial ecology;

## 1. Introduction

Ehrlich and Holden (1971), who introduced the original form of the IPAT equation,  $i = p \cdot f$ , where  $i$  is environmental impact,  $p$  is the population and  $f$  is the per capita impact, concluded that ‘population control, the redirection of technology, the transition from open to closed resource cycles, the equitable distribution of opportunity and the ingredients of prosperity must all be accomplished if there is to be a future worth having’. Graedel and Allenby (1995) published the first textbook on industrial ecology, in which they adopted the following IPAT variant as the “master equation” (Chertow, 2000):

$$i = p \times a \times t, \quad (1)$$

where  $i$  represents environmental impact,  $p$  is the population,  $a$  is the ratio of GDP to population, and  $t$  is the ratio of  $i$  to GDP.

In their textbook, they state, that ‘although the master equation should be viewed as conceptual rather than mathematically rigorous, it can be used to suggest goals for technology and society’. Note that  $p$  and  $a$  in eq. (1) are more accessible to researchers than the  $t$  term, which becomes the residual of an accounting identity (i.e.  $t = i/pa$ ) (Chertow, 2000).

Chertow (2000) mentioned that ‘[a]lthough the IPAT equation was once used to determine which single variable was the most damaging to the environment, an industrial ecology view reverses this usage, recognizing that increases in population and affluence can, in many cases, be balanced by improvements to the environment offered by technological systems’. Meanwhile, Ehrlich et al (1971) stated that ‘complacency concerning any component of these problems—sociological, technological, economic, ecological—is unjustified and counterproductive’.

Life cycle assessment (LCA) is a major research area in the field of industrial ecology, which also includes industrial metabolism, dematerialization, eco-design, and industrial symbiosis (ISIE, 2009). Inventory analysis in LCA, called life cycle inventory analysis (LCI), can be expressed as in eq. (2), which bares some resemblance to the master equation (Heijungs, 2001).

$$\text{Environmental intervention} = \text{Intervention matrix} \times \text{Technology matrix}^{-1} \times \text{External demand} \quad (2)$$

The technology and intervention matrices in LCI, which correspond to  $t$  in the master equation, are no longer the residual, but exogenous variables given by physically measured data. Most models of the functional-unit-based LCA form do not consider affluence or population aspects, while the major

issues analyzed in the Club of Rome report were of the types with increasing population, increasing affluence, and constant technology (Heijungs et al, 2008). Furthermore, in the eco-efficiency literature, the focus has been more on the role of technology rather than that of affluence and population. For instance, Huppes and Ishikawa (2009) wrote, ‘technologies will play a dominant role in economic development as well as in environmental quality, resource requirements and resource depletion’. By contrast, their discussion on de-growth (i.e. producing and consuming less) involves a relatively stronger focus on affluence and population, with the statement that de-growth ‘could be part of a cultural development towards a slower, more leisurely society’, and that de-growth with a given population means ‘lower affluence, relative to the reference’.

This paper argues that this ‘reverse’ indicated by Chertow (2000) took place when LCI started to be used in conjunction with the IPAT equation, which enabled not only decomposition analysis but also marginal analysis. This will be clarified by formulating the equations for both analyses of LCI.

Meanwhile, any effort (regardless of failures) to formulate an equation for decomposition analysis in the dynamic Leontief model will illuminate the concept of growth mechanism, which has been missing in the static tools of industrial ecology such as the IPAT equation and LCA.

Comparing mathematically and computationally these two different models in a simple setting will explain the difference between an economic system driven by production and one by consumption, which will provide an additional, clearly defined discussion point for Sustainable Consumption and Production (SCP).

## **2. Problem Definition and Research Questions**

In LCI, intervention and technology matrices, and external demand are exogenous, and result in environmental intervention (see eq. (2)). As defined and analyzed in detail subsequently, the structure of this equation enables us to determine the contribution of change in each variable to the total change of the environmental intervention between two periods in the past (decomposition analysis). It also enables us to predict the degree of change in the environmental intervention caused by changes in the variables in the future (marginal analysis).

The mathematical formulations of the two analyses quantitatively clarify the meaning of ‘reverse’, since the marginal analysis is related to the notion: ‘increases in population and affluence can, in many cases, be balanced by improvements to the environment offered by technological systems’. This leads to the question whether the ‘reverse’ of Chertow (2000) is identified among the equations of decomposition and marginal analysis in LCI. [Research Question 1].

In static LCI, the decrease in population and affluence (thus external demand) and the

improvement in technology lead to emission reduction. In addition, arguments on the rebound effect may be added, e.g., Hertwich (2005a); people may use more light bulbs and/or consume other products more when the bulbs/products are more energy efficient.

However, in such static models, an important mechanism has been forgotten; the growth of the economy due to surplus. In LCI, if the technology matrix and external demand are fixed, the production level is statically stable. There is no growth in the economy, which might not be the case in reality as suggested by the dynamic Leontief model as shown in this paper. Because, even when there are no changes in external demand and technology, positive/negative growth of the economy may exist, resulting in changes in the emissions. Thus, the following questions are posed: Does technology that efficiently uses energy and materials lead to lesser or greater environmental impact? [Research Question 2]; Does lesser consumption affect the environment less or more? [Research Question 3].

Even though LCI is mathematically equivalent to the static Input Output Analysis (IOA) (Heijungs and Suh, 2002), and both the static and dynamic IOA were invented by Leontief, the static/dynamic models can give different answers to the same questions. In such a case, how can we interpret the different behavior of the static and dynamic models? [Research Question 4].

In the following sections, I define and analyze the static LCI and dynamic Leontief models in order to answer these questions.

### 3. LCI and analogy to IPAT equation

The mathematical structure of LCI is shown below as a hypothetical model of two processes, two commodities, and one emission:

$$T_{out} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, T_{in} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix}, B = [b_1 \quad b_2], \tilde{f} = p \times a \times \tilde{y}, \tilde{y} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}, \tilde{q} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$$

where  $T_{in}$  and  $T_{out}$  are the input/output technology matrices. They mean that process 1 produces 1 kg of commodity 1 from  $t_{11}$  kg of commodity 1 and  $t_{21}$  kg of commodity 2, and that process 2 produces 1 kg of commodity 2 from  $t_{12}$  kg of commodity 1 and  $t_{22}$  kg of commodity 2. Note that the technology matrix in LCI is ordinarily defined as  $T_{out} - T_{in}$ , but here I define them separately in order to use them in the dynamic model in the next section.

$B$  is the intervention matrix, meaning that  $b_1$  kg of pollutant is emitted when 1 kg of

commodity 1 is produced and that  $b_2$  kg of pollutant is emitted when 1 kg of commodity 2 is produced.  $\tilde{f}$  is the external demand that consists of the population ( $p$ ), the affluence factor ( $a$ ), and the basic consumption per capita ( $\tilde{y}$ ). A person consumes  $ay_1$  kg of commodity 1 and  $ay_2$  kg of commodity 2. Multiplied by population, this becomes the external demand ( $\tilde{f}$ ) for the whole economy. A similar formulation has been already introduced in the LCA literature, e.g., Heijungs et al (2008). When a population increases, the external demand also follows proportionally. This also applies to the affluence factor.  $\tilde{q}$  is the total output vector:  $q_1$  kg of commodity 1 from process 1 and  $q_2$  kg of commodity 2 from process 2 are produced. Then, given the external demand, and the technology and intervention matrices, the total output vector and environmental intervention (i.e., emission),  $i$ , is derived as follows:

$$\tilde{q} = (T_{out} - T_{in})^{-1} \times \tilde{f} \quad (3),$$

$$\tilde{i} = B \times \tilde{q} = B(T_{out} - T_{in})^{-1} \times p \times a\tilde{y} \quad (4).$$

The total output level is determined by the external demand and the technology matrix. Being different from the dynamic Leontief model, the model assumes all production is for meeting the external demand, thus there is no room for surplus in economic growth, i.e.,  $\tilde{q} - T_{in}\tilde{q} = \tilde{f}$ . Eq. (4) can be considered equivalent to the master equation. The environmental intervention,  $\tilde{i}$ , corresponds to the environmental impact,  $i$ , of the master equation, although the impact here simply means the amount of pollutants released (i.e., emissions) or resources extracted rather than damage or human risk. The latter is analyzed in another phase of LCA, the impact assessment. The population is represented by  $p$  in LCI and the master equation. The affluence factor multiplied by the basic consumption per capita,  $a\tilde{y}$ , corresponds to the affluence of the IPAT equation. Technology in IPAT equation corresponds to  $B(T_{out} - T_{in})^{-1}$  in LCI, which is defined as the intensity matrix,  $\Lambda = B(T_{out} - T_{in})^{-1}$  (Heijungs and Suh, 2002). Since  $p$ ,  $a$ ,  $T_{in}$ ,  $\tilde{y}$  and  $B$  are all positive, eq. (4) indicates that the environmental intervention decreases when the population, the affluence factor, and the coefficients of  $B$  and  $T_{in}$  (i.e., technology) decrease [the answers to Research Question 2 and 3 in LCI]. The behavior of this equation resembles that of the master equation of

Industrial Ecology (as suggested by Heijungs and Suh, 2002).

The decomposition analysis of LCI between time  $t-1$  and  $t$  is written as follows:

given  $B_{t-1}$ ,  $(T_{in,t-1} - T_{out,t-1})$ ,  $\tilde{f}_{t-1}$ ,  $B_t$ ,  $(T_{in,t} - T_{out,t})$  and  $\tilde{f}_t$

$$\tilde{i}_{t-1} = B_{t-1} (T_{in,t-1} - T_{out,t-1})^{-1} \tilde{f}_{t-1} \quad (5)$$

$$\tilde{i}_t = B_t (T_{in,t} - T_{out,t})^{-1} \tilde{f}_t$$

$$\Delta \tilde{i} = \Delta B \times (T_{in,t} - T_{out,t})^{-1} \times \tilde{f}_t + B_{t-1} \times \Delta T^{-1} \times \tilde{f}_t + B_{t-1} \times (T_{in,t-1} - T_{out,t-1})^{-1} \times \Delta \tilde{f} \quad (6)$$

where  $\Delta \tilde{i} = \tilde{i}_t - \tilde{i}_{t-1}$ ,  $\Delta B = B_t - B_{t-1}$ ,  $\Delta T^{-1} = (T_{in,t-1} - T_{out,t-1})^{-1} - (T_{in,t} - T_{out,t})^{-1}$  and

$$\Delta \tilde{f} = \tilde{f}_t - \tilde{f}_{t-1}$$

Given  $B_{t-1}$ ,  $(T_{in,t-1} - T_{out,t-1})$ ,  $\tilde{f}_{t-1}$ ,  $\Delta B$ ,  $\Delta T^{-1}$ , and  $\Delta \tilde{f}$ , the marginal analysis of LCI between  $t-1$  and  $t$  is expressed as,

$$\tilde{i}_t = B_t (T_{in,t} - T_{out,t})^{-1} \tilde{f}_t = (B_{t-1} + \Delta B) \left( (T_{in,t-1} - T_{out,t-1})^{-1} + \Delta T^{-1} \right) (\tilde{f}_{t-1} + \Delta \tilde{f}) \quad (7)$$

where  $B_t = B_{t-1} + \Delta B$ ,  $(T_{in,t} - T_{out,t})^{-1} = (T_{in,t-1} - T_{out,t-1})^{-1} + \Delta T^{-1}$  and  $\tilde{f}_t = \tilde{f}_{t-1} + \Delta \tilde{f}$ .

The equations of decomposition and marginal analyses in LCI are mathematically the same (because (5) + (6) = (7)) but also there is a subtle difference in their operation. In decomposition analysis, firstly,  $B_t$ ,  $(T_{in,t} - T_{out,t})$ , and  $\tilde{f}_t$  are given, then  $\tilde{i}_{t-1}$  and  $\tilde{i}_t$  are calculated, and finally  $\Delta \tilde{i}$  is decomposed into parts with  $\Delta B$ ,  $\Delta T^{-1}$  and  $\Delta \tilde{f}$ . Meanwhile, in marginal analysis,  $\Delta B$ ,  $\Delta T^{-1}$ , and  $\Delta \tilde{f}$  are firstly given and then  $\tilde{i}_t$  is calculated.

The ‘reverse’ of Chertow (2000) exists between these two analyses: eq. (6) determines the



contribution of change in each variable to the total change of the environmental intervention between two periods in the past. Moreover, eq. (7) predicts the future environmental intervention caused by the change in the variables [the answer to Research Question 1].

In the next section, the static model is converted into the dynamic.

#### 4. Dynamic Leontief model and surplus, consumption and growth

In 1953, Wassily Leontief published a dynamic version of his input-output model (Fleissner, 1990), which is an open dynamic model in the sense that consumption is exogenous. Earlier, Neumann (1945) introduced a closed dynamic model, which has mathematical and theoretical similarities with the dynamic Leontief model, and the unique eigenvalue of the technology matrix was interpreted as growth and interest rate (Inoue, 2001). The latter is out of the scope of this paper.

Considering the similarities in the mathematical structure of LCI and the Input Output Analysis (Heijungs and Suh, 2002), this section expresses the discrete dynamic model with eq. (8) by introducing the capital matrix,  $C$  :

$$C = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}$$

$$T_{out}\tilde{q}_{(t)} - T_{in}\tilde{q}_{(t)} - C(\tilde{q}_{(t+1)} - \tilde{q}_{(t)}) = \tilde{f} \quad (8).$$

The meaning of the capital matrix is that  $c_{11}$  kg of commodity 1 and  $c_{21}$  kg of commodity 2 shall increase in capital when the output of commodity 1 increases by 1 kg between times  $t$  and  $t+1$  (i.e.,  $q_{1(t+1)} - q_{1(t)} = 1$ ) and that  $c_{12}$  kg and  $c_{22}$  kg shall increase when the output of commodity 2 increases by 1 kg between  $t$  and  $t+1$ . The surplus allocated to other than consumption,  $T_{out}\tilde{q}_{(t)} - T_{in}\tilde{q}_{(t)} - \tilde{f}$ , is not zero in general, in contrast to the static LCI and IOA, and this surplus is invested into capital. Eq. (8) is rewritten as eq. (9), which means that the total output vector may increase/decrease with time even when the external demand and technology matrices are fixed:

$$\tilde{q}_{(t+1)} = C^{-1}((T_{out} - T_{in} + C)\tilde{q}_{(t)} - \tilde{f}) \quad (9).$$

The marginal analysis of the external demand is conducted as follows:

given  $\Delta \tilde{f}$

$$\Delta \tilde{q}_f = -C^{-1} \Delta \tilde{f} \quad (10)$$

where  $\tilde{q}_{(t+1), with \Delta f} = C^{-1}((T_{out} - T_{in} + C)\tilde{q}_{(t)} - (\tilde{f} + \Delta \tilde{f}))$  and  $\Delta \tilde{q}_f = \tilde{q}_{(t+1), with \Delta f} - \tilde{q}_{(t+1)}$ .

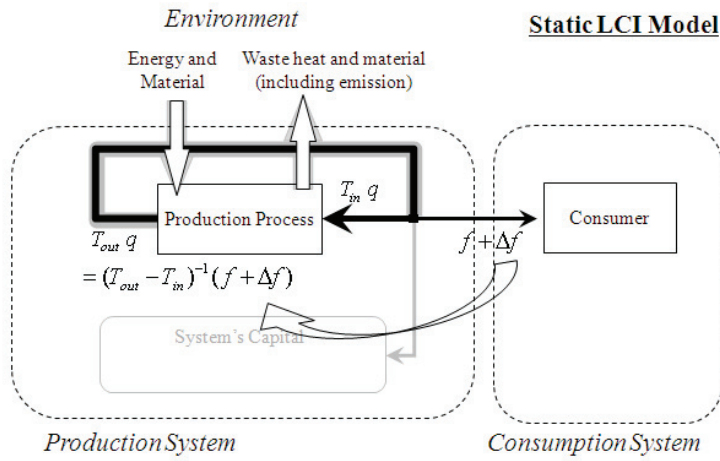
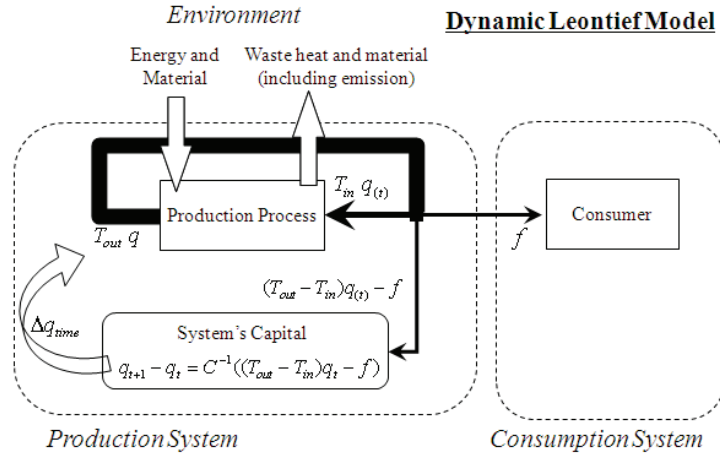
Note that this marginal analysis compares the cases  $q_{(t+1), with \Delta f}$  and  $q_{(t+1)}$  in the same period (i.e., time  $t+1$ ) and not between time  $t$  and  $t+1$  as in the marginal analysis of LCI.

Relative to the decomposition analysis of LCI, the change in the total output vector between times  $t$  and  $t+1$  is as follows by eq. (8):

$$\Delta \tilde{q}_{time} = \tilde{q}_{(t+1)} - \tilde{q}_{(t)} = C^{-1}(T_{out} \tilde{q}_{(t)} - T_{in} \tilde{q}_{(t)} - \tilde{f}) \quad (11).$$

From this equation, the change in the total output cannot be decomposed into other exogenous variables as in the decomposition analysis of LCI; the total output vector at time  $t$  drives its change.

The difference between the static LCI and the dynamic Leontief models is schematically shown in Figure 2.



**Figure 2. The  $\Delta\tilde{q}_{time}$  of the dynamic Leontief model and the  $\Delta\tilde{f}$  of the static LCI model as the driver for each system.**

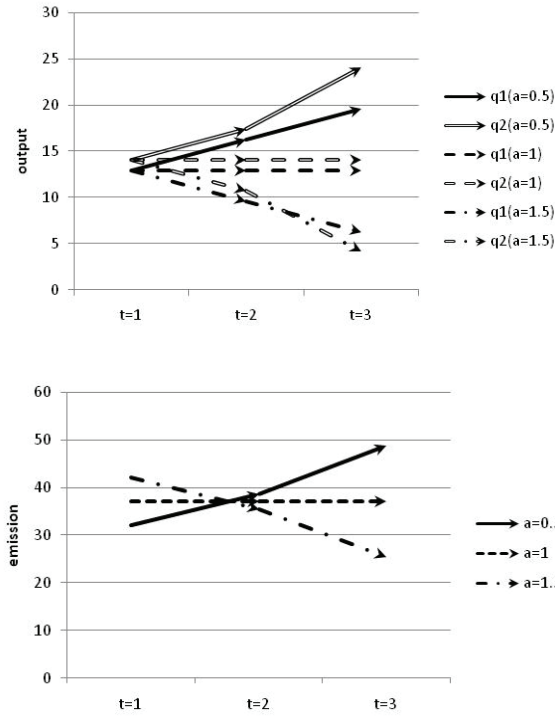
Figure 1 shows that the driver for all the energy and material flows in the dynamic Leontief model is the endogenous  $\Delta\tilde{q}_{time}$  term in the production system (see eq. 11). In contrast, in the static LCI model the driver is the exogenous  $\Delta\tilde{f}$  term in the consumption system (see eq. 3). It is also worth considering the effect of the change in the external demand in the dynamic Leontief model (see eq. 10). As depicted in the bottom side of Figure 2, if the driver is not in the consumption but in the production system, the efforts to reduce energy and material flows through the control of the external demand may affect only parts of the total flows. In contrast to the behavior of LCI, eq. (10) suggests that a decrease in the external demand may result in an increase of the output vector.

Instead of analyzing the general mathematical properties of eq. (9), a numeric example is used to demonstrate what happens when the environmental impact increases with time and the external demand decreases. The affluence factor is set to range between 0.5 and 1.5. Three periods are calculated. Longer periods are not considered, partly because the model results start to oscillate. The latter suggests an unstable system (see Fleissner, 1990 for more discussion on the stability of the dynamic Leontief model). Finally,  $\tilde{q}_{(1)}$  is set as  $\tilde{q}_{(1)} = (T_{out} - T_{in})^{-1}10\tilde{y}$  and for  $a = 1$  zero growth is achieved (i.e.,  $\tilde{q}_{(t+1)} - \tilde{q}_{(t)} = 0$ ) since surplus allocated to other than external demand is zero.

$$T_{out} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, T_{in} = \begin{bmatrix} 0.3 & 0.5 \\ 0.5 & 0.4 \end{bmatrix}, B = [1 \quad 1], C = \begin{bmatrix} 0.1 & 0.2 \\ 0.2 & 0.1 \end{bmatrix}$$

$$\tilde{q}_{(1)} = \begin{bmatrix} 12.94117647 \\ 14.11764706 \end{bmatrix}, \tilde{y} = \begin{bmatrix} 0.2 \\ 0.2 \end{bmatrix}, p = 10, a = 0.5, 1 \text{ or } 1.5.$$

Total environmental interventions are calculated, with those of the consumption stage, under the assumption that when the external demand vector is  $\tilde{f} = [2 \quad 2]^T$  (ex.  $\tilde{y} = [0.2 \quad 0.2]^T$ ,  $p = 10$  and  $a = 1$ ) 10 units of emissions are released. Then, the total emissions at time  $t$  are,  $\tilde{i}_{(t)} = B \times \tilde{q}_{(t)} + pa$ . Figure 2 shows the results of the total output vectors and the emissions. In period 1, the emissions are higher when the external demand is higher (i.e.,  $a$  is higher), and the order is the same as that in the static LCI. Note that when  $a = 0.5$ , more commodities are produced to satisfy the demand in that period, i.e., surplus for growth. This enables the economy to accumulate capital and leads to positive output growth in the next period. When  $a = 1.5$ , fewer commodities are produced to satisfy the demand in that period, and that makes the economy to use capital to supplement the demand and leads to negative output growth in the next period. Thus, in period 3, the order of the emissions output is overturned; lesser consumption results in greater future growth and emissions, and greater consumption results in lesser future growth and emissions [the answers to Research Question 3 in the dynamic Leontief model]. The same result is obtained when population,  $p$ , ranges between 5, 10, and 15 while the affluence factor is fixed at 1, since the external demand is defined by basic consumption multiplied by population and affluence.



**Figure 3. Total output and emissions with different external demand.**

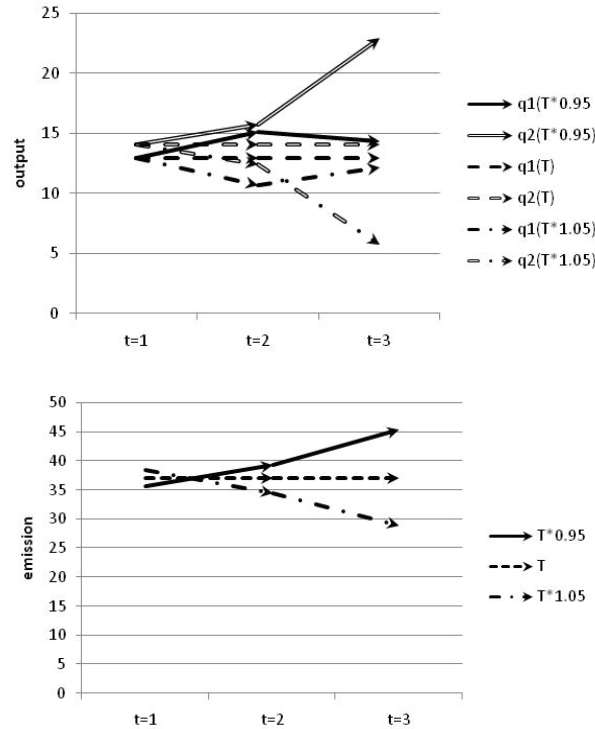
A similar trend is observed when changing the input technology matrix,  $T_{in}$ . The coefficients of the matrix remain in constant proportional as they decrease and increase. At  $T_{in, 0.95}$ , in order to produce a certain commodity, intermediate inputs decrease by 5% compared with  $T_{in, 1}$  whereas technology is more efficient.  $T_{in, 1.05}$  is the situation of a less efficient technology. The affluence factor remains fixed at 1.

$$T_{in, 0.95} = 0.95 T_{in, 1} \text{ and } T_{in, 1.05} = 1.05 T_{in, 1},$$

$$a = 1.$$

Figure 4 shows the results of the total output vectors and emissions. In period 1, the emissions are higher when the technology efficiency is higher, which is consistent with the results of LCI. However, higher efficiency means that the output exceeds the demand in this period (i.e., surplus for growth), resulting in capital accumulation which enables greater production and emissions in the next period. Note that the oscillation is already observed in the total output in period 3, and this trend

is not clear. However, the results suggest that a more efficient technology may increase future production and emissions [the answers to Research Question 2 of the dynamic Leontief model].



**Figure 4. Total output and emissions with different input technology matrix.**

These results clarify the importance of surplus,  $T_{out} \tilde{q}_{(t)} - T_{in} \tilde{q}_{(t)}$ , which is allocated between external demand and capital investment for growth. In this example, the consumption is fixed and when the surplus exceeds it, the system grows; expansion of the economy with greater environmental intervention takes place in the future.

## 5. Conclusion and Discussions on Sustainable Consumption and Production

Starting from the IPAT equation, whose variants are adopted as the “master equation” in industrial ecology (Chertow, 2000), and based on the resemblance of the inventory analysis of the static LCA (LCI) with the IPAT equation (Heijungs, 2001), the LCI and the dynamic Leontief model are compared under similar conditions.

Considering the first research question and the statement of Chertow (2000), “an industrial

ecology view reverses this usage, recognizing that increases in population and affluence can, in many cases, be balanced by improvements to the environment offered by technological systems”, this “reverse” is identified to exist between the decomposition and marginal analyses of LCI (see eqs. (6) and (7)).

Regarding the second research question, “*does technology that efficiently uses energy and materials lead to lesser or greater environmental impact?*”, it is shown that more efficient technology coefficients lead to lesser emissions in the static LCI. Furthermore, a numeric example of the dynamic Leontief model results in greater future production and emission via growth of the system; the answer may vary depending on the chosen model that is driven by either production or consumption. Likewise, for the third question, “*does lesser consumption affect the environment less or more?*”, lesser consumption leads to emission reduction in the static LCI, in contrast, it may result in greater future production and emission via growth in the dynamic Leontief model.

With respect to the final question, “*how can we interpret the different behavior of the static and dynamic models?*”, one answer is that the static LCI has the driver for energy and material flows in the consumption system as an external demand. In contrast, the dynamic Leontief model has it in the production system with a surplus generating mechanism allocated between consumption and investment (Figure 2). The literature on sustainable consumption and production is reviewed for further discussion.

The field of industrial ecology field needs to pay greater attention to the dynamic mechanism, which states that smaller consumption may lead to greater future growth and environmental intervention, especially in the debate of sustainable consumption and production. Hertwich (2005a) doubts that the neoclassical growth or general equilibrium models used by energy economists have much to contribute to sustainable consumption research. It is not clear in his argument whether the neoclassical growth model also includes the growth mechanism embedded in the dynamic Leontief model or not. However, considering the fact that the dynamic Leontief model is the extension of the static LCI, which is one of the core methodologies of industrial ecology and whose variables are consistent with the IPAT master equation, the statement seems to acknowledge the importance of the growth mechanism in the dynamic Leontief model. It is also noteworthy that this dynamic mechanism is not about the substitution and income effects researched in the static general equilibrium model. In contrast, the dynamic model, framed in this paper, excluded such substitution effects from its logic by using a linear production function and affluence factor that is proportional to the consumption level of each commodity. Even in such a setting, the growth mechanism remains and smaller consumption may result in greater future environmental intervention.

An interpretation of “sustainable consumption” is the effort to reduce the impact of the affluent (Hertwich, 2005b) and it has to be discussed further. Munksgaard et al. (2005) cite and

interpret a statement of Adam Smith under the sustainable consumption context whereas the static IOA is used in their analysis. “In accordance with Adam Smith’s classical statement that “consumption is the sole end and purpose of all production” (Smith [1776] 1904, Vol. II Book IV), these indirect requirements are ultimately being demanded by the households”. In the dynamic Leontief model, the production surplus is not only for external consumption but also for growth capital investment. From the point of view of the dynamic model, the future production growth and the consumption of the future generations in addition to the consumption at present are both the end and purpose of production.

Sustainable Consumption researchers have been preoccupied with finding out why consumers want to consume ever more and whether this is good for them (Hertwich, 2005a). Meanwhile, the dynamic Leontief model suggests that if consumers can consume more there will be no room for capital growth and, consequently, for future production output. This leads to a paradigm shift from “why do consumers want to consume more?” to “why society cannot consume to the point where the environmentally destructive growth of capital and production is prevented?”, or into “why do consumers have to consume in a productive way in order for producers to grow more?”. Another view claims that the consumption level is already more than what they want; Lebel (2005) describes a situation where consumers cannot say “enough!”, because “multinational companies have gained almost full control of the retailing of food and household goods across Asia, and indeed much of the globe”. Monetary aspects (e.g., how prices are determined in the model) are not discussed in this paper, but it is reasonable to argue that such companies will not respond to “enough!”. Because, in order to be successful in corporate terms, they have to increase revenue; reduce costs; and, thereby, achieve a healthy profit margin. All that for funding the investment needed to ensure the future survival-the sustainability-of the company-, and to provide the dividends that shareholders expect; the promise of which has persuaded them to invest their capital in the company (Jackson and Clift, 1998). This situation is described as consumers “locked into” unsustainable patterns of consumption, either by social norms that lie beyond the control of the individual, or else by the constraints of the institutional context within which an individual choice is executed. This emphasizes that these circumstances are “often deliberately created by producer and business interests” (Jackson, 2005).

This paper does not support the opinion that producers can/must solve these problem by themselves or that by encouraging people to consume excessively (specially combined with overworking) reduces future environmental emissions and achieves de-growth. It simply poses a question: if consumption or/and production are to be reduced (i.e., de-growth) in order to solve environmental problems, then, there is a logical contradiction between the static model that is driven by the external demand of consumption and the dynamic Leontief model that is based on production. How shall we deal with this contradiction? Specifically, is it possible to reduce consumption and production at the same time in any dynamic mode?



One way to challenge these questions is to discuss about other possible uses of the surplus produced by the economy. For instance, part of surplus can go to environmental purposes rather than excessive consumption and capital production, which is related to the arguments on weak and strong sustainability. If “strong sustainability” is needed, minimum amounts of a number of different types of capital (economic, ecological, social) should be independently maintained, in real physical/biological terms (Ayer et al, 1998), and this maintenance will need a part of the surplus.

Another way is to recall the fact that consumers in a consumption system are simultaneously laborers and shareholders in production systems. For example, a work-sharing mechanism introduced in several countries may result in lesser labor inputs as capital in a production system and lesser consumption because of smaller income (though other income sources in the case of shareholders may exist).

A tragedy contrary to that of “enough!” is also observed in current pre-industrialized societies, which may be compared under the context of sustainable consumption and production. In a society in Samoa, economic activity through ritual has an important role. Kin groups have rituals of “exchange” between them. This is not like money exchange and whatever is exchanged is unproductively consumed on the scene of the ritual. Without this unproductive consumption, a kin cannot keep their face in society with other kin. This even goes to the extent that it threatens their daily subsistence. However, regardless of this, the head of a kin admits that even though it is painful they cannot stop from doing it (Yamamoto and Yamamoto, 1996). Here, social demands of pure consumption (i.e., external demand in the dynamic model) are so high that they do not allow wealth accumulation. This contrasts with the view of Lebel (2005) on modern society, “a world has been created where success is measured by wealth accumulation and where goods are the standards for social comparison, class identification, and power labeling”.

In addition to that, on external demand, the marginal analysis on technology improvement can be mathematically formulated (eq. (10)) and when the two are combined with  $\Delta\tilde{q}_{time}$ , this is written as:

$$\Delta\tilde{q} = \Delta\tilde{q}_{time} + \Delta\tilde{q}_f + \Delta\tilde{q}_T = C^{-1} (T_{out}\tilde{q}_{(t)} - T_{in}\tilde{q}_{(t)} - \tilde{f}) - C^{-1}\Delta\tilde{f} - C^{-1}\Delta T_{in}\tilde{q}_{(t)} \quad (12).$$

Eq. (12) explains, first, the mechanism of a “production” system, second, the impact of “consumption”, and, third, the effect of “technology” improvement. This equation suggests that, at least, these three elements, production, consumption and technology, have to be considered simultaneously in order to analyze the dynamic flows of energy and materials in the economy.

This equation is similar to the differential equation of the dissipative systems or the Lotka-Volterra (prey-predator) model though it does not show the clear negative feedback loop

mechanism with the consumption system as the predator. Monetary and market mechanisms might work as a force to structure the system through this irreversible (thus not static) process. As shown in Neumann (1945), the technology matrix,  $(T_{out} - T_{in})$ , has a unique eigenvalue which equals growth and interest rates. However, it might be difficult to discuss negative growth (i.e., producing and consuming less), since money hardly depreciates and interest rates cannot be negative in general.

It is worth considering why a dissipative system is helpful to understand human society. One answer is that a physical system with energy and material flows will behave as in eq. (12) if such a dynamic view holds true. Another answer may be that society needs it for its values regardless of its physical base. In addition to a social meaning of consumption,  $-C^{-1}\Delta\tilde{f}$ , as shown in the example in Samoa, that of  $-C^{-1}\Delta T_{in}\tilde{q}_{(t)}$  can be also considered. Even when productions efficiencies are not maximized, and if people find social meaning for a lesser efficiency, this is a possibly desirable path for society. For instance, the concept of “appropriate technology” that empowers people from a social perspective may be worth revisiting (Schumacher, 1973).

## 6. References

- Ayer, R. U., J. C. J. M. van den Bergh and J. M. Gowdy. 1998. Viewpoint: Weak Versus Strong Sustainability, Tinbergen Institute Discussion Papers, number 98-103/3.
- Chertow, R. M. 2000. The IPAT Equation and Its Variants: Changing Views of Technology and Environmental Impact, *Journal of Industrial Ecology*, 4(4): 13-29.
- Ehrlich, P. and J. Holden. 1971. Impact of population growth, *Science*, 171, 1212-17.
- Fleissner, P. 1990. Dynamic Leontief Models on the Test Bed, *Structural Change and Economic Dynamics*, 1(2): 321-357.
- Graedel, T. and B. Allenby. 1995. *Industrial ecology*. Englewood Cliffs, NJ: Prentice Hall.
- Heijungs, R. 2001. *A theory of the Environment and Economic Systems: a unified framework for ecological economic analysis and decision-support*, Edward Elgar Publishing, Inc.

Heijungs, R. and S. Suh. 2002. *The computational structure of life cycle assessment*, Kluwer Academic Publishers.

Heijungs, R., G. Huppes and J. Guinée. 2008. *A Scientific Framework for LCA*, Deliverable D15 of the CALCAS project.

Hertwich, E.G. 2005a. Consumption and the Rebound Effect: An Industrial Ecology Perspective, *Journal of Industrial Ecology*, 9(1-2): 85-98.

Hertwich, E.G. 2005b. Consumption and Industrial Ecology, *Journal of Industrial Ecology*, 9(1-2): 1-6.

Huppes, G., M. Ishikawa. 2009. Eco-efficiency guiding micro-level actions towards sustainability: Ten basic steps for analysis. *Ecological Economics*, 68 (6), 1687-1700.

Eco-efficiency guiding micro-level actions towards sustainability: Ten basic steps for analysis. *Ecological Economics*, 68 (6), pp. 1687-1700.

Inoue, H. 2001. *Linear Economics*, Tokyo, Hakutoh (in Japanese).

ISIE, 2009. Web page of International Society for Industrial Ecology. <http://www.is4ie.org/history> (accessed on 07/04/2009)

Jackson, T. and R. Clift. 1998. Where is the profit in industrial ecology?, *Journal of Industrial Ecology*, 2(1): 3-5.

Jackson, T. 2005. Live Better by Consuming Less? : Is There a "Double Dividend" in Sustainable Consumption? , *Journal of Industrial Ecology*, 9(1-2): 19-36.

Lebel, L. 2005. Transitions to Sustainability in Production-Consumption Systems, *Journal of Industrial Ecology*, 9(1-2): 11-13.

Munksgaard, J., M. Wier, M. Lenzen, and C. Dey. 2005. Using Input-Output Analysis to Measure the Environmental Pressure of Consumption at Different Spatial Levels, *Journal of Industrial Ecology*, 9(1-2): 169-185.

Neumann, J.V. 1945. A Model of General Economic Equilibrium, *The Review of Economic Studies*, 13(1):1-9.

Schumacher, E. F. (1973) *Small Is Beautiful: A Study of Economics As If People Mattered*

Smith, A. 2009. An inquiry into the nature and causes of the wealth of nations. 1776. The Project Gutenberg EBook. <http://www.gutenberg.org/files/3300/3300-h/3300-h.htm> (accessed on 07/04/2009)

Yamamoto, T. and Yamamoto, M. 1996. *Economy as rituals: Gift giving, Power, and Sexuality in Samoan Society*, Tokyo, Kobundo (in Japanese).

## **CHAPTER 3**

### **Industrial Pollution in a Petrochemical Area, Data Accessibility and Elaboration from a Public Perspective:**

#### **A Case Study in Gela, Sicily**

##### **Abstract**

The aim of this work is to consider which type of information can be retrieved from public database to evaluate industrial pollution. This work illustrates the case of the petrochemical industrial site of Gela (Sicily, Italy) where there are several activities subject to the IPPC Directive. This paper analyses the characteristics of this Directive and defines the methodological issues to implement the IPPC Directive in a real case study. An LCA and air pollution modeling was carried out using public data from the EPER and other sources in order to show the possibilities and limits to access and use public available data. In this paper we will also address the issue of integration of different data, scales and methodologies, that is at the core of the development of any analysis of the impacts of industrial activities on environment and health.

##### **Keywords**

LCA; IPPC; Refinery; Dispersion; Air Pollution; EPER

## 1. Introduction

The aim of this work is to consider which type of information can be retrieved from public database to evaluate industrial pollution. This work also illustrates the procedure for the application of the Life Cycle Assessment (LCA) methodology to the case of the petrochemical industrial site of Gela in Sicily (Italy) where a large petrochemical complex is subject to the Directive on Integrated Pollution Prevention and Control (IPPC). In this paper we will consider the IPPC Directive - 96/61/EC (EC, 2008a)<sup>3</sup> adopted in Italy in 2005 (Ministero dell'Ambiente e della Tutela del Territorio, 2005), its methodological perspectives and implications.

An LCA and an air pollution modeling were run to show the possibilities and limits of available public data from the European Pollutant Emission Register (EPER) and other sources (e.g. air pollution monitoring stations). LCA is defined by an international standard (ISO 14040/44) and it allows both an assessment of direct impacts (i.e. emissions from industrial plants in the area) and indirect impacts (i.e. emissions occurring outside the area of production). In this paper, only the direct impacts were taken into account, because LCA is utilized as a tool to support strategic decisions to adopt BAT (Best Available Techniques), as requested by the IPPC.

Some questions will be also raised on the issue of integration. In particular it is important to consider integration as a way of moving from a segmented vision to a more comprehensive one including multiple media (i.e. water, air and soil), production-emission chain, and different space/time scales.

## 2. The IPPC Directive

Until very recently, the division of environmental regulations according to water, air and soil and the separated administrative and monitoring treatments did not allow a global vision of environmental crisis and an optimal capacity of interventions. To tackle these problems the European Union issued the Directive 96/61/CE, IPPC, integrally adopted in Italy in year 2005 (Ministero dell'Ambiente e della Tutela del Territorio, 2005).

Different approaches to controlling emissions into the air, water or soil separately may encourage the shifting of pollution between the various environmental media rather than protecting the environment as a whole (EC, 2008a: introduction 8).

This Directive, according to the principles regulating environmental EU policy, aims at

---

<sup>3</sup> The Directive was approved in 1996 (EC, 1996). It was recently abrogated and re-codified as Directive 2008/1/EC, by including all the previous amendments and introducing some linguistic changes and adaptations. In the text we will refer to EC (2008a) to mention the IPPC Directive.

preventing, reducing, and, as far as possible, intervening directly to the source of pollution according to the principle of pollution prevention. The IPPC Directive is one of the most ambitious legal measures that the European Union (EU) has initiated with a view to applying the prevention principle for industrial activities (Barros et al., 2006).

The necessity to deal with highly complex systems of production and pollution has led to the need to consider more “integrated” approaches. In the IPPC Directive there is an important mention to two kinds of integrations. The first one can be defined as “horizontal integration”, considering all the relevant pollutants, all the media (i.e. air, water, soil) and all the important environmental impacts to be put together. The Directive states “the objective of an integrated approach to pollution control is to prevent emissions into air, water or soil wherever this is practicable, taking into account waste management” (EC, 2008a: introduction 9). The second kind of integration can be defined as “vertical integration”. The Directive declares: “emission limit values [ELVs], parameters or equivalent technical measures should be based on the best available techniques (BAT)” (EC, 2008a: introduction 18), thus mentioning the need to integrate production processes and emissions. This Directive suggests an extended meaning for “emissions”, as emissions include the whole technological cycle: “the direct or indirect introduction, as a result of human activity, of substances, vibrations, heat or noise into the air, water or land” (EC, 2008a: Article 2.2).

In this Directive we can identify three core principles related to Vertical Integration, each of which corresponds to three stakeholders (industrial operator, public and competent authority) and to current scientific knowledge: (1) BAT, (2) public participation and (3) flexibility (EC, 2008b). The first principle, BAT, is targeted at industrial operators. The permit conditions, including ELVs, must be based on BAT, as defined in the IPPC Directive. BAT is of direct interest for industrial operators as BAT is one of the key elements affecting production - emission chain. BAT can be defined as the most effective measure in the development of an activity providing the basis for ELVs designed to prevent or eliminate or to reduce an emission and its impact on the environment as a whole (Mirasgedis et al., 2008). BAT must comply with the planning instruments adopted in each single territory (Ministero dell’Ambiente e della Tutela del Territorio, 2005). The second relevant point is about public participation. “Public has a right to participate in the decision making process, and to be informed of its consequences, by having access to, (a) permit applications in order to give opinions, (b) permits, (c) results of the monitoring of releases and (d) the European Pollutant Emission Register (EPER)”. Thus, while the public’s direct concern is health and other environmental impacts, it can also be involved in the control of the upper stream of the chain (i.e. concentration – emission- production). It has to be considered that “public” is a general label meaning not much. The public action in this kind of problem is linked to the possibility not only to access data, but also to mobilize authorities, experts, laboratories etc. The third principle, flexibility, is related to government activities. IPPC Directive allows flexibility for the licensing authorities (i.e. regional

authority) in determining permit conditions, “to take into account a) the technical characteristics of the installation, b) its geographical location and c) the local environmental conditions”. All these points are related to the possibility of accessing data and information. It is then critical to consider which data are available.

## 2.1. The European and Italian Pollutant Emission Registers

BREFs (best available techniques reference documents: (<http://eippcb.jrc.ec.europa.eu/pages/FActivities.htm>)) for production processes and EPER (European Pollutant Emission Register: [www.eper.cec.eu.int/eper](http://www.eper.cec.eu.int/eper)) for emissions are the two fundamental documents supporting the IPPC. In fact: “An inventory of the principal emissions and sources responsible shall be published every three years” (EC, 2000). As mandated by the IPPC, a national inventory of emissions and their sources, *Inventario Nazionale delle Emissioni e loro Sorgenti* (INES), was set up in Italy. INES is a part of the EPER. The EPER and the Italian national register INES contain qualitative and quantitative information on air and water emissions originated by the main productive sectors and big size plants. Current information available in EPER for Italy is referred to 2002 and 2004. INES is yearly updated and in year 2008 information is available for the years 2002, 2003, 2004 and 2005.

The regulation No 166/2006 by the EU established an integrated and coherent European Pollutant Release and Transfer Register in the form of a publicly accessible electronic database ([www.prtr.ec.europa.eu](http://www.prtr.ec.europa.eu)). This regulation was proposed to carry into effect the UNECE Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (Aarhus Convention, 1998)<sup>4</sup> and to improve public access to environmental information and a more effective participation by the public in environmental decision-making. In the next future, the Pollutant Release and Transfer Registers (PRTR) will replace the EPER (EU, 2006). PRTR builds on the same principles as EPER, but goes beyond, by including reporting on more pollutants, more activities, releases to land, releases from diffuse sources and off-site transfers.

## 3. The road to an integrated approach: some questions

Our work was targeted to an investigation of the impacts to air pollution of a large refinery complex

---

<sup>4</sup> The Aarhus Convention on “Access to Information, Public Participation in Decisionmaking and Access to Justice in Environmental Matters” was adopted at the Fourth Ministerial Conference “Environment for Europe” in Aarhus, Denmark, on 25 June 1998. Thirty-nine countries and the European Community have ratified it.



in Gela in Sicily starting from an LCA for the territory and a dispersion modeling for air pollutants. At the beginning of the investigation it was decided to build an integrated approach. During the recent years the issue of integration was addressed with several proposals. The integration can be pursued over a large range of approaches going from a theoretical discussion on the categories, definition and input and output of different models, until the construction of an integrated software or device. The attempt to integrate different chains of effects generates a number of questions to be answered. Raising questions is fundamental step in building an integrated approach (Canter and Kamath, 1995). Some fundamental questions were translated into a check list, taking into account the IPPC Directive (see Tab. 1).

**Tab. 1: List of general questions regarding integration in risk assessment**

|  |
|--|
| Spatial Boundary   |
| S1. Are proper geographical issues addressed? How is identified the area at risk?                  |
|  |
| Temporal Boundary  |
| T1. From which year, should the data of flows of pollutants be gathered?                           |
| T2. Are historical stocks as well as yearly flows of pollutants in different media considered?     |
|  |
| Vertical Integration   |
| V1. Is the mechanism between production, technology and emission clearly understood?               |
| V2. Is the relation between emission and concentration of pollutants in media clearly established? |
| V3. Does the exposure from concentration to targets at risk get clarified?                         |
| V4. Does the exposure fully explain the damage of targets (e.g. in terms of health effects)?       |
|  |
| Horizontal Integration   |
| H.1 Are the whole location of emissions (i.e. point source, non-point source) considered?          |
| H.2 Are the entire emission of pollutants covered?   |
| H3. Are all the pathways through different media (i.e. air, water and soil) examined?              |
| H4. Are the whole range of risks on each target (e.g. people, agricultural field) considered?      |
| H5. Are locations, pollutants, pathways and targets at risk considered simultaneously?             |
| H6. Are important synergetic or antagonistic reactions taken into account?                         |

The S1 issue is a well-known problem that if not tackled can produce ambiguous results, just considering the Modifiable Areal Unit Problem (MAUP). The temporal series of data available is relevant, when considering the time-lag of many diseases. Both space and time scales have to be

considered intertwined<sup>5</sup> and a potential solution to modifiable scale problem would be to clarify both scale choice and scale effects, that is the extent that results could be manipulated according to the size of the area studied in relation to cumulative effects assessment (Karstens, 2007). To complete the categorization of the issue to be tackled we also considered vertical and horizontal integration. Each connection of the whole chain, from production to impacts, needs to be associated (vertical integration), while in each stage, all the emissions sources, pollutants emitted, pathways through media and targets in risk must be systematically treated and related (horizontal integration).

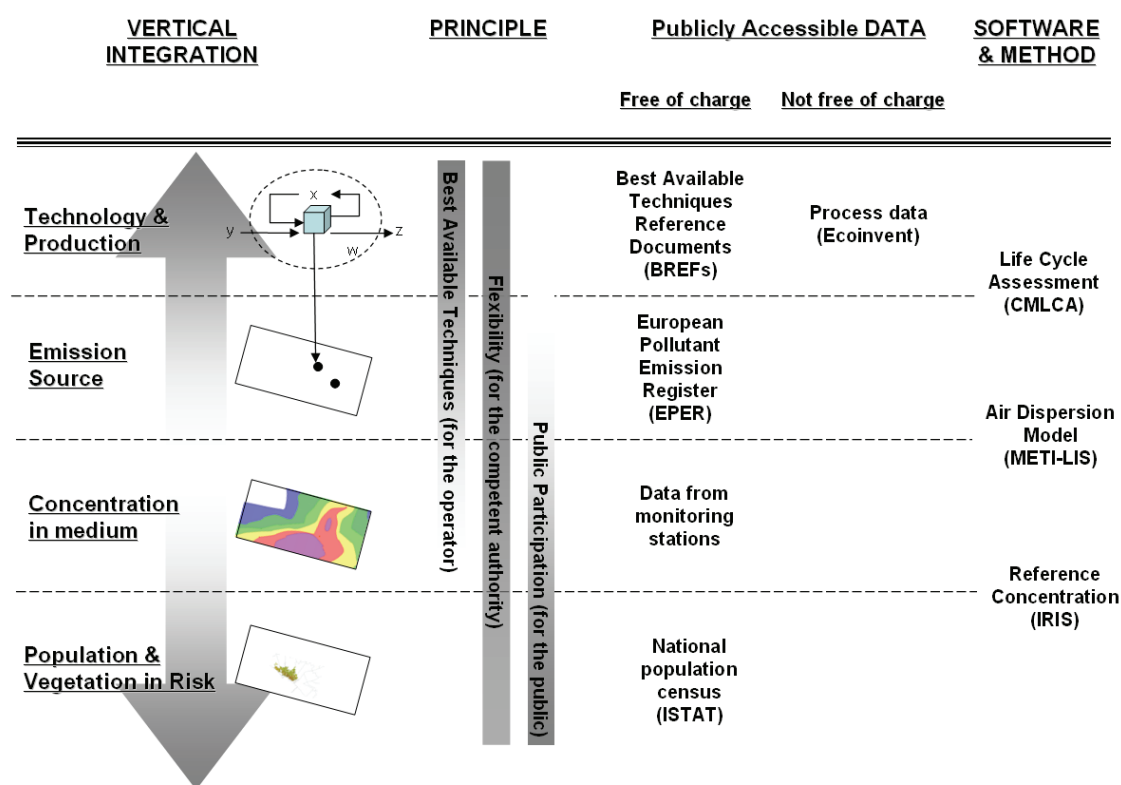
An interesting way to integrate different methodologies is by mean of a Geographic Information System (GIS). Integration of risk assessment and spatial planning using GIS capabilities can improve the efficiency of contaminated land management (Bień et al., 2005). Evaluation of the potential risks associated with existing industrial activities involve importing and exporting datafile produced by standalone existing tools or an application that integrates the risk analysis tools with the general-use GIS program (Hellweger et al., 2002).

#### **4. Public available data: IPPC and Methodologies**

The IPPC Directive takes into account the position of three stakeholders: industrial operator, competent authority and public. Although this is a very simplified triangular vision, we can use it as a starting point, assuming the perspective of the public. It is worth mentioning that this “public” perspective must be operationalized and contextualized and it involves which expertise to be put at stake in assessing complex phenomena. Based on a real case study, another question to be tackled immediately emerges: to which extent can public have access, comprehensively understand and utilize the data in the integrated manner to participate in the decision making process and to be informed of its consequences? To undertake the question of public access and integration of different information, the data and software, i.e. operational methods, have to be selected, following precise criteria: (1) all the data to be used are publicly accessible, (2) preferably public data free of charge are used, (3) among public data, web-accessible data without any request are used rather than data available on formal written request, and (4) all the software to be used should be free of charge for public use. In the case study, three software and methods were selected, and five dataset were used (see Figure 5).

---

<sup>5</sup> Notice that LCA is primarily designed to analyze networks of production activities, rather than environmental risk of a certain space and time on which such activities take place. However, space and time themselves are the main issues to be considered for the decisions based on IPPC Directive.



**Figure 5. Data and Software that public can use for IPPC methodologies**

A software for LCA, Chain Management by Life Cycle Assessment (CMLCA, version 4.2), developed by the Institute of Environmental Sciences (CML), Leiden University, the Netherlands, has been chosen (free of charge for non-commercial purposes only). CMLCA allows considering the consistency of data between production and emission. Notice that LCA normally analyzes all the processes (i.e. from cradle to grave), but in our case only the processes and emissions occurring in the area (i.e. direct impacts) were considered. It is worth considering that LCA can only provide rough estimates for risk assessment, because of the need to simplify spatial and temporal variety in each area.

Quantitative data of industrial process are needed to fill the gap between production and emission and to run a LCA. In the IPPC Directive, public is supposed to have access to permit applications in order to give opinions (EC, 2008a: preamble 27). BREFs contain rich information on technology, but it is difficult to link production and emission data, in quantitative terms, for a specific site. To solve this problem, Ecoinvent database (version 1.2) was used to assess how production and emission were quantitatively connected. Ecoinvent is one of major supplier of life cycle inventory data, its database contains up-to-date and consistent life cycle inventories for approximately 4000 industrial processes.

In the IPPC Directive, certain industrial plants must report their emissions to the air and

the water through the EPER, which is publicly accessible. The emission data calculated by LCA based on processes and outputs of products can be compared to the emission data reported by EPER. By this comparison, it can be investigated whether the two data are consistent or not, and whether introducing a better techniques in a certain process contribute to the reduction of emissions.

In order to identify which pollutants are of relevance the DG Environment of the EC refers to the Annex III in the Directive 96/61/CE, to the EPER (INES in Italy) and to the already available BREFs. At the European level, documents of reference are: “Integrated Pollution Prevention and Control: Reference Document on the Best Available Techniques for Mineral Oil and Gas Refineries and the Italian equivalent for BREFs (Italian Decree 127/2007). Based on the DG Environment suggestions we made a first selection of pollutants linked to the technological cycle operating in Gela (see Tab. 2).

**Tab. 2 - Pollutants originated by oil refineries selected for analysis**

|                  |   |
|------------------|---|
| Air pollutants   | Particulate Matter, PM10, CO, NOx, SOx, PCDD/F, Metals and Compounds (Cu, Pb, As, Ni, Cd, Zn, Cr, Hg, Sn), H2S, NH3, VOC, Benzene                 |
| Water pollutants | Suspended particles, COD, BODn, TOC, Total Nitrogen, Total Phosphor, Metals and Compounds, Hydrocarbons, Phenol, Benzene, Cyanide, Sulphurs, MTBE |

We have chosen an air dispersion model, METI-LIS program (version 2.03, free of charge to public)<sup>6</sup>. The emission data from EPER, together with meteorological and elevation data and data on the heights of chimneys, are input into METI-LIS resulting in dispersion data in the ambient air. The modeled dispersion results can be compared to the measured concentration data from monitoring stations. Furthermore, dispersion maps can be layered with population data from national census, and allow to identify where and which population get affected by particular concentrations. Reference Concentration method in IRIS (Integrated Risk Information System) by USA-EPA can be useful for this purpose.

By using free software and established methodologies, it should be possible to identify the impact of a large industrial complex and make proposals about the management of emissions (e.g. types of emissions to be reduced, height of chimney, location, and timing of emissions).

<sup>6</sup> METI-LIS was developed by the Ministry of Economy, Trade and Industry of Japan, based on ISC model (US-EPA), with improved parameterization after new experiments, including basic GIS. This software and its manuals are provided in English as well as in Japanese.

## 5. The case of Gela in Sicily

The 31 December 2006, according to the population registers, Gela has 77 311 inhabitants. This means that Gela ranks sixth in Sicily after Palermo, Catania, Messina, Siracusa and Marsala. The area of Gela is formed by a big urban center, a large industrial area and an extensive agricultural land use. The refinery in Gela is the 8th in Italy in terms of charge capacity. Gela refinery was built in 1960 and in 1962 the plants started their activities refining 3 Mt/year of oil. Currently it works and transforms more than 5 Mt/year of oil, more than 20% is constituted by local oil. The industrial area covers approximately 5 sq km. In 2001, Gela and the municipalities of Butera and Niscemi was recognized by the Italian state as a “high environmental risk area” which implies the mandate for the local government to start cleaning polluted zones and rehabilitate the territory (Ministero dell’Ambiente e della Tutela del Territorio, 1990; 2000). In Gela, there is a system of 6 monitoring stations, managed by the Provincia Regionale of Caltanissetta, where the concentrations of SO<sub>2</sub> in the air, partially originated from the petrochemical plants, are hourly recorded. Data from 5 stations were analyzed<sup>7</sup>. The stations are classified in three cases as “urban”, in one case “rural” and “industrial”. High concentrations of Ni, V and, partly, Ba and Cr in road dust were associated with emissions from the petrochemical plant (Manno et al., 2006). Another study on the chemical composition of airborne particulate matter over the town of Gela found out that the petrochemical plant appears to be associated with raised levels of As, Mo, Ni, S, Se, V, and Zn (Bosco et al., 2005). Threshold limit values were exceeded for some carcinogenic pollutants: heavy metals (e.g. As, Ni, Cr, Cd, V, and Hg), hydrocarbons, BTEX, chlorinated-derivatives of aliphatic compounds, halogen-derivatives of aliphatic compounds, polycyclic aromatic hydrocarbons (PAHs) in soils (Paris, 2007). Furthermore, threshold limit values were exceeded for heavy metals, polycyclic aromatic hydrocarbons, Methyl Tertiary Butyl Ether (MTBE), chlorinated-derivatives of aliphatic compounds, BTEX in the water table. In the water table, concentrations of As were registered with a value of 70 000 µg/l vs. a threshold equal to 10 µg/l, concentrations of mercury reached the value of 6 600 µg/l compared to a threshold limit of 1 µg/l (Paris, 2007). In Gela, to complete the picture, there is an excess of cancer pathologies both for men and women either for mortality and morbidity (Fano et al., 2005).

Following the IPPC Directive, the main objective of the Gela case study has been to examine what is feasible with public data. In particular the aims of the case study in Gela are: 1) to run an LCA, 2) to run dispersion models, 3) to give information on likely impacts from the industry.

In order to estimate to which degree these objectives were achieved, if we go back to the checklist presented in Tab. 1, it is interesting to see how it can be filled according to the criteria we

---

<sup>7</sup> In total, there are eight monitoring stations in the area, among which NO<sub>2</sub> is measured in the two, CO in the four, O<sub>3</sub> in the two, NMHC in the two, PM<sub>10</sub> and Benzene in the one.

introduced in the previous paragraph about the question of public access and integration of different information. The work followed three steps: 1) addressing the general questions regarding integration that we summarized in Tab. 1; 2) carrying out LCA for the Gela refinery; 3) selecting pollutants to be compared.

First, the questions of the check list were answered (see Tab. 3). It was decided to work with the emission data resulting from the petrochemical activity in the main industrial area. The data available covered the period 2002-2005. Emissions and concentrations in the air were considered. Emission into water is also registered in EPER, but not considered to select pollutants since there were not enough data available to run water dispersion model to calculate concentration. Data on the chemical characterization of soil were not considered because they were not available at the time of the study and only results from non systematic investigations were available.

**Tab. 3 Check Lists for IPPC, applied to Gela case**

|   |
|---|
| Spatial Boundary  |
| S1. Among the area concerning industrial activities in Gela, the area managed by ENI company is chosen (other industrial areas in Gela are not relevant). The industrial area is clearly delimited by a natural park, a highway, a river and the sea.   |
| Temporal Boundary   |
| T1. The available data of 2002-2005 were chosen (emissions from past years not included)  |
| T2. Historical stocks of pollutants in the environment were not available.  |
| Vertical Integration  |
| V1. In the case of Gela, only the output of production was available, just from crude oil, without the flows of all chemicals. Ecoinvent's process data were supplemented to analyze production-emission chain.   |
| V2. METI-LIS dispersion model was used to relate emission and concentration in the air (not into water or soil).  |
| V3. Location of population was identified. Rough exposure to air pollution is possible. Exposure through water, soil or food is difficult with available data.  |
| V4. Only carcinogenic risk from inhalation exposure (E-6, IRIS) is considered to evaluate the result of the air dispersion model. In LCA, a much broadly defined health effect, human toxicity potentials, is used.   |
| Horizontal Integration  |
| H.1 Two sites of point source registered in EPER. Linear source (e.g. road traffic) was not considered.   |
| H.2 In LCA the entire emission of pollutants can be fairly enough covered. From EPER we have 50 pollutants (some are missing, e.g. V). In air pollution monitoring only selected pollutants are measured (ex. SO <sub>x</sub> , NO <sub>x</sub> ). In Reference Concentration (RfC), not all the important pollutants have reference value. |
| H3. The pathway through air was examined, but not through water and soil.   |
| H4. Only the risk of population was considered, not agricultural field, fish and other animals.   |
| H5. 2 locations (nearby sites registered in EPER), 13 pollutants through air, population were considered simultaneously.  |
| H6. Synergetic or antagonistic reactions were not taken into account.   |

Although we faced several limitations to a complete application we found very interesting results.

## 5.1. Emission data quality issues

LCA focusing on direct emission on the area was carried out for the Gela refinery by CMLCA

software using the database of Ecoinvent (2005). To define the degree of the final output vector of economic flows, highly aggregated data (eg. the production amounts of Benzene, Gasoline and Liquid Petroleum Gas all aggregated) specific for the Gela refinery were available (Eni divisione Refining & Marketing, 2007). Thus, it was assumed that 13 kinds of petrochemical products were produced equally in ratio (i.e. bitumen, two kinds of diesel, heavy fuel oil, kerosene, light fuel oil, two kinds of naphtha, two kinds of petrol, petroleum-coke, propane/butane, and refinery gas, 7.7% for each product). For the process data, the refinery's own process data to run LCA were not publicly available, thus it was supposed that the processes are the same of Ecoinvent, where 137 petrochemical processes are assumed to take place in Gela. The emissions only from this area called direct emissions. Ecoinvent covers more than 2000 kinds of environmental emissions<sup>8</sup>, among which 142 emissions are relevant in this LCA for Gela. EPER covers 50 pollutants to be reported, among which, 23 pollutants are actually reported by the Gela refinery.

13 pollutants (CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, Benzene, Phenol, As, Cd, Cr, Cu, Hg, Ni, Zn, V) were chosen for comparing LCA's calculated emissions and EPER's registered emissions. Among these only V is not included in the 50 pollutants to be registered in EPER, though according to LCA results V is also important and should be considered in particular for human toxicity effects. Metals are particularly relevant because they are adsorbed within particulate matter, fine PM<sub>2,5</sub> and PM<sub>10</sub>. Also notice that in EPER emissions are registered only if their emissions exceed certain threshold values, while in LCA emissions always appear regardless of any threshold.

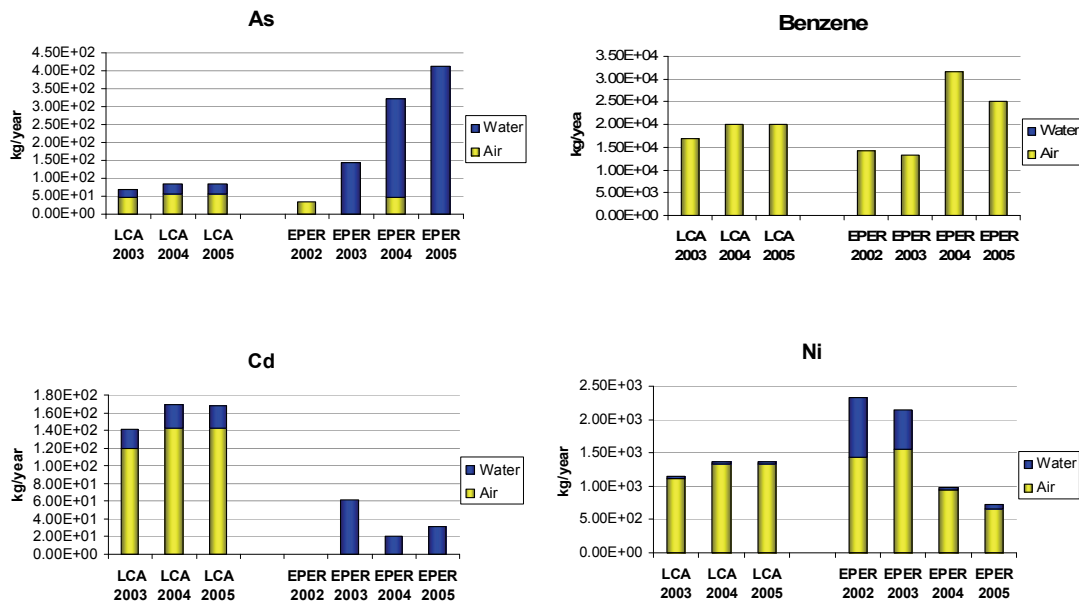


Figure 6. Comparison of calculated (by LCA) and reported (to EPER) emission data

<sup>8</sup> Emission into air, water and soil is considered as different emission, even when the substance of the emission is the same

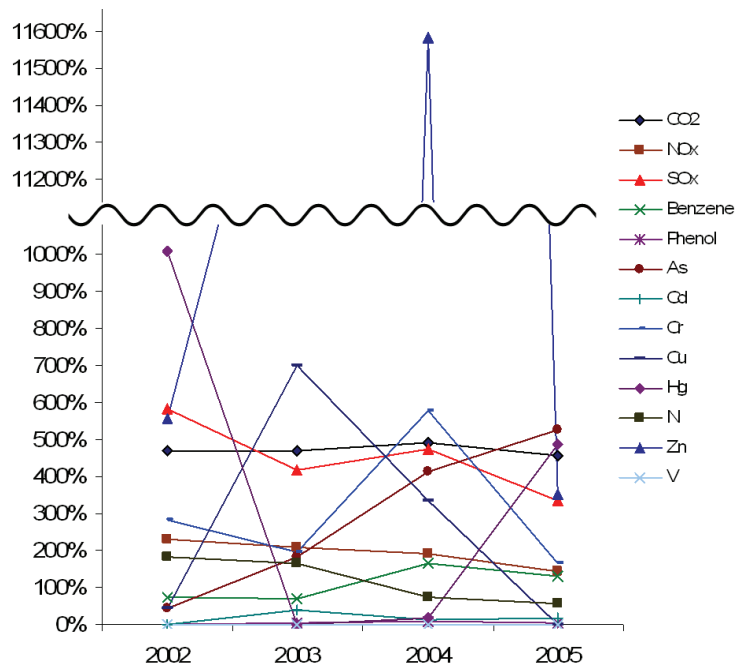


The comparison of 4 important pollutants (well-known cancerogenous agents with no threshold without effects on human health), Cd, As, Ni compounds and benzene is shown in Figure 6 (NB LCA for 2002 was not calculated because of no available data on production output for that year). These pollutants are subject to a specific regulation by the European Union (EC, 2004; 2008c). The results from the LCA and the EPER registered emission data appear inconsistent. We need to consider two points about this inconsistency. First, before comparing the calculated and reported data, the EPER's data itself has to be analyzed critically; the rather big fluctuation of the registered data has to be explained, since the production of the refinery is relatively stable, this is why LCA result is more stable, while abatement technologies might have changed. Assuming that there is no big technological change, it is very difficult to explain why the As reported emission is increasing rapidly, Benzene emission is fluctuating, Ni emission is decreasing, and emission into water almost disappearing. These trends deserve a more careful control and investigation that were out of the scope of the current investigation.

Second, by comparing LCA and EPER, it can be observed that it would be better if data on production and data on process get publicly available more quantitatively in detail. The LCA run in this case is an example what can be elaborated from the public data, but it is not possible to judge whether the registered data are wrong or the calculated one (or both). In the current EPER reporting system, only emission data are registered. If data on production, data on process and information about each change for abatement technologies are also publicly registered it would be possible for "third parties" to run LCA to check the consistency between production and emission, and eventually this type of contradiction we found might be solved as well as the fluctuation of registered data.

It is highly difficult for authority to determine emission limit values (ELVs) without officially obtaining data for each process and production of each specific industrial operator and without understanding the degree of cause and effect between process, production and emissions, since ELVs should be based on best available techniques (BAT) according to the IPPC Directive.

In Figure 7, emissions (those into air and water are aggregated) are depicted. If EPER's registered data were stable, yearly up and down of each line should be diminished (or explained by technology change). Meanwhile if there exists consistency between LCA and EPER, each line must get close to 100% because the average value of LCA (2003-2005) is set as 100%. From this figure, neither of them is observed.



**Figure 7. EPER's yearly fluctuation and the scale difference from LCA's data (=100%), for each pollutant**

## 5.2. Emission, dispersion and monitored concentration data

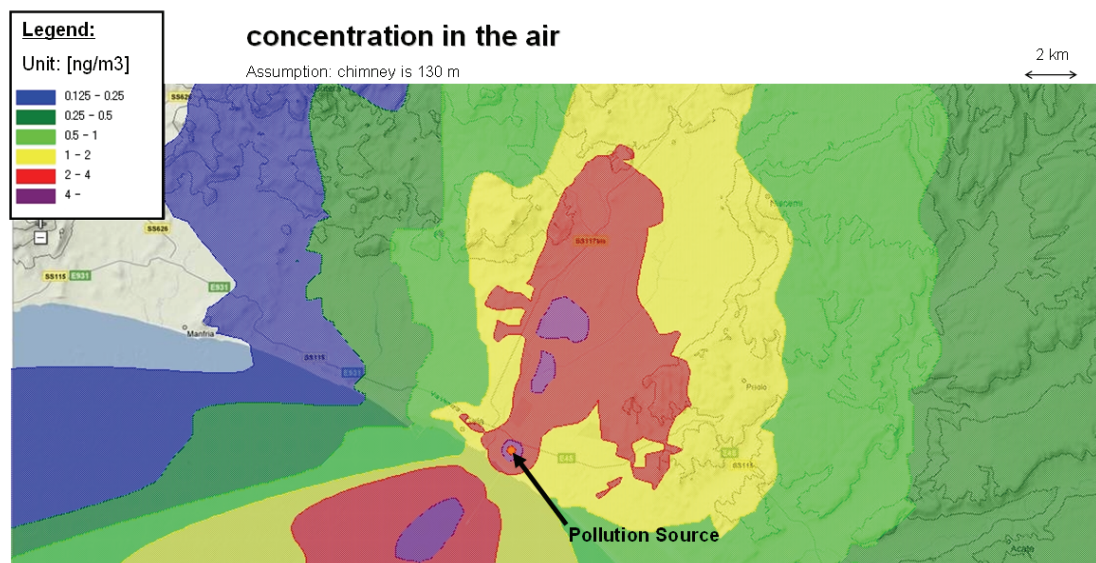
We ran a dispersion model, METI-LIS, to calculate concentrations of pollutants in the ambient air for emission data from EPER and LCA. The heights of chimneys vary in the Gela Refinery (ex. 10m, 15m, 20m, 30m, 90m, 130m at maximum).

The data available from INES, did not show which amount of any pollutant is emitted from the different chimneys. For this reason, two cases were assumed in the dispersion model: all the emissions are from a chimney, (1) height of 30m and (2) height of 130m. Operational data (i.e. at what time the refinery is working) was not obtained, thus it is assumed as 24 hours operation (i.e. the total production is equally distributed in time). This is an assumption that could lead to some kind of underestimate or overestimate. For example, we could have an underestimate of night pollution and overestimate of daily pollution if there are peaks of emissions at night with stable atmospheric conditions. Gela is facing the sea, wind blowing in the opposite direction between day and night (from south-west to north-east during day and vice versa during night). Thus the more they operate during daytime, the more the region in the north-east from the refinery would get affected by emissions. For Meteorological data (i.e. wind direction and strength, solar radiation and temperature for 365 days\*24hours) the monitoring station data of 2004 in Gela was used as input into the

dispersion model for all elaborations. The elevation data of the area was also used as input.

Among the targeted 13 pollutants, the air emission levels for 12 pollutants from Gela Refinery were selected (no phenol emissions into air). For the air emissions of two pollutants, V and Cd, there are no data reported in EPER, thus LCA results (maximum value from 2004 data elaboration) were used. For the other 10 emissions, the maximum values reported in EPER (and declaration of emissions, which is national reporting system corresponding to EPER) in 2002 - 2005 were chosen. The election of the maximum value ensures an evaluation of the worst possible conditions. In Gela area, there is another site (Polimeri Europa Spa) registered in EPER, which emits Benzene and NO<sub>x</sub> to the air. These emissions were added to those of Gela Refinery. These two sites are close to each other, thus when in running the dispersion model it was assumed that they stand in the same location.

In LCA hundreds of pollutants are often considered, in EPER 50 pollutants are registered and the air quality monitoring system in Gela covers a limited number of pollutants (i.e. SO<sub>2</sub>, NO<sub>2</sub>, CO, O<sub>3</sub>, NMHC, PM<sub>10</sub> and Benzene). Even in such a situation, the concentration of V in the air can be calculated through LCA and the air dispersion model, though this pollutant is not registered in EPER and is not monitored in Gela (Figure 8).

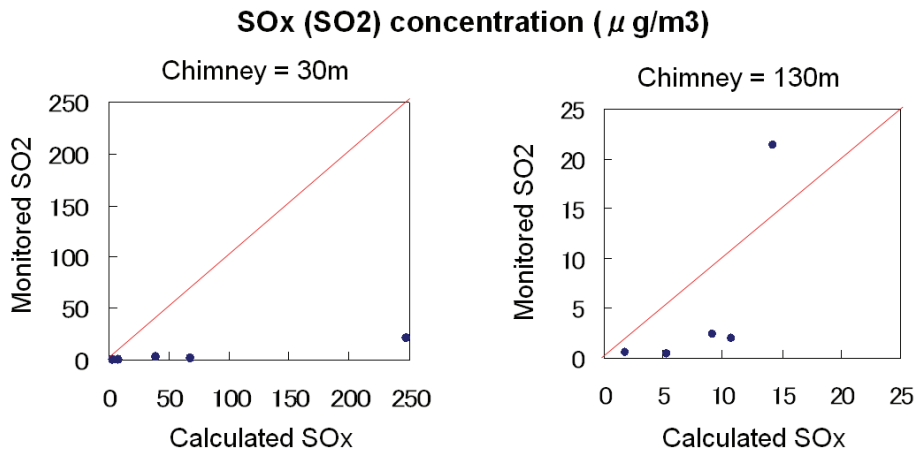


**Figure 8. Concentration of V calculated from LCA and METI-LIS**

The areas particularly affected by the results of the simulation appeared to be the north-eastern agricultural ones. This, if confirmed by environmental monitoring controls, would imply an increase of the concentrations of V in the air and a potential growth in concentration of V also in the soil, with a likely influence on the food chain. V affects food chain through contaminating a variety of

foods with a relatively low efficiency but in sufficient quantities to be absorbed at detectable levels in many body tissues (Bharti et al., 1990). V is released on oil combustion to generate electric power and introduced into the environment during the extraction of petrochemical products and in the production of steels and insecticides (Colina et. al., 2005).

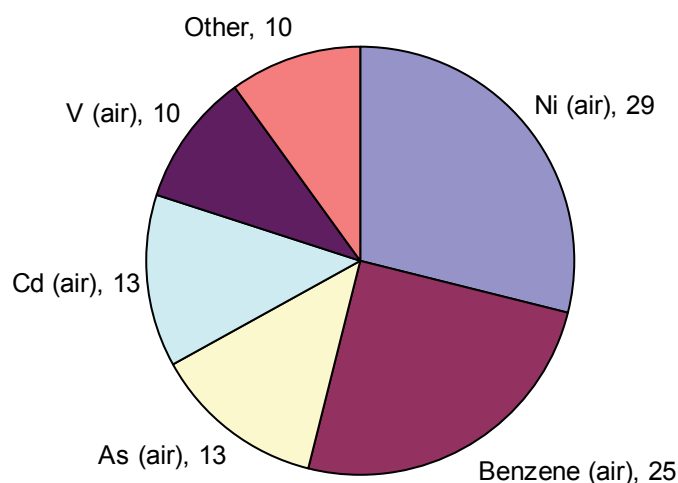
SO<sub>2</sub> monitored concentration data by monitoring stations were compared to SO<sub>x</sub> concentrations (SO<sub>2</sub> + SO<sub>3</sub>) calculated with the dispersion modeling (METI-LIS). SO<sub>2</sub> is monitored in stations managed by the Provincial Authority. Comparisons are based on two assumptions: all the SO<sub>x</sub> emissions are from chimney of (1) 30 m in height and (2) 130 m in height (Figure 9). Elaborations based on the latter assumption give more consistent results between monitored and calculated data. When monitoring and modeled data are perfectly correlated all the points should lie on the diagonal lines (see Figure 9). This is not the case.



**Figure 9. SO<sub>x</sub> (SO<sub>2</sub>) concentration monitored by 5 stations and calculated by METI-LIS**

### 5.3 Risk to humans

The procedures of LCA can provide inventory analysis and also input for interesting impact assessment exercises, in terms of human toxicity assessment linked to air pollution inhalation. To calculate human toxicity from emission inventory data, the linear coefficients of Human Toxicity Potentials (HTP<sub>inf</sub>) (Huijbregts et al., 1999 and 2000) adopted by CMLCA, was used (for further detail see Guinée, 2002). The results of LCA suggest that five air emissions, Ni, Benzene, As, Cd, and V, are the largest potential contributors to human toxicity and they are all carcinogens (see Figure 10). Other includes 57 pollutants, among them, for example, Se (air), Cr VI (air), Co (air), Cu (air), HF (air), NO (air), Se (fresh and marine water) (see Figure 10).



**Figure 10. Contribution of each emission from the refinery to human toxicity caused by the refinery (%), calculated by LCA methodology**

Regarding non-cancerogenous pollutants, air quality guidelines indicates the level of air pollutant concentrations, associated to time of exposure, that do not have adverse health effects (WHO, 2006). For cancerogenous pollutants we can use the unit of risk. The incremental unit risk estimate for an air pollutant or drinking water is defined as the additional lifetime cancer risk occurring in a hypothetical population in which all individuals are exposed continuously from birth throughout their lifetimes to a concentration of 1  $\mu\text{g}/\text{m}^3$  of the agent in the air they breathe or to 1  $\mu\text{g}/\text{L}$  in water (see US-EPA website)<sup>9</sup>. The results of calculations expressed in unit risk estimates provide the opportunity to compare the carcinogenic potency of different compounds and can help to set priorities in pollution control, taking into account current levels of exposure (WHO, 2000). IRIS (Integrated Risk Information System) of US-EPA is available on the web, to determine the unbearable concentration threshold. For As, Benzene, Cd and Ni, IRIS's Reference Concentration, Quantitative Estimate of Carcinogenic Risk from Inhalation Exposure, E6 (1 in 1 000 000) was selected.

As, Benzene, Cd and Ni were the four biggest impacting pollutants elaborated using data from the LCA (Figure 11). The area in purple color means that the concentration is above the threshold of E6 (1 in 1 000 000). If all the emissions are from lower chimneys, 30m in height, the concentrations of these pollutants in Gela city are getting closer to these thresholds, according to the

<sup>9</sup> The interpretation of unit risk for a substance in drinking water would be as follows: if unit risk =  $2 \times 10^{-6}$  per  $\mu\text{g}/\text{L}$ , 2 excess cancer cases (upper bound estimate) are expected to develop per 1,000,000 people if exposed daily for a lifetime to 1  $\mu\text{g}$  of the substance in 1 L of drinking water (see US-EPA website).

results of this dispersion model (Figure 11). In these maps, densely populated areas (Gela, Niscemi and Manfria) are colored in black.

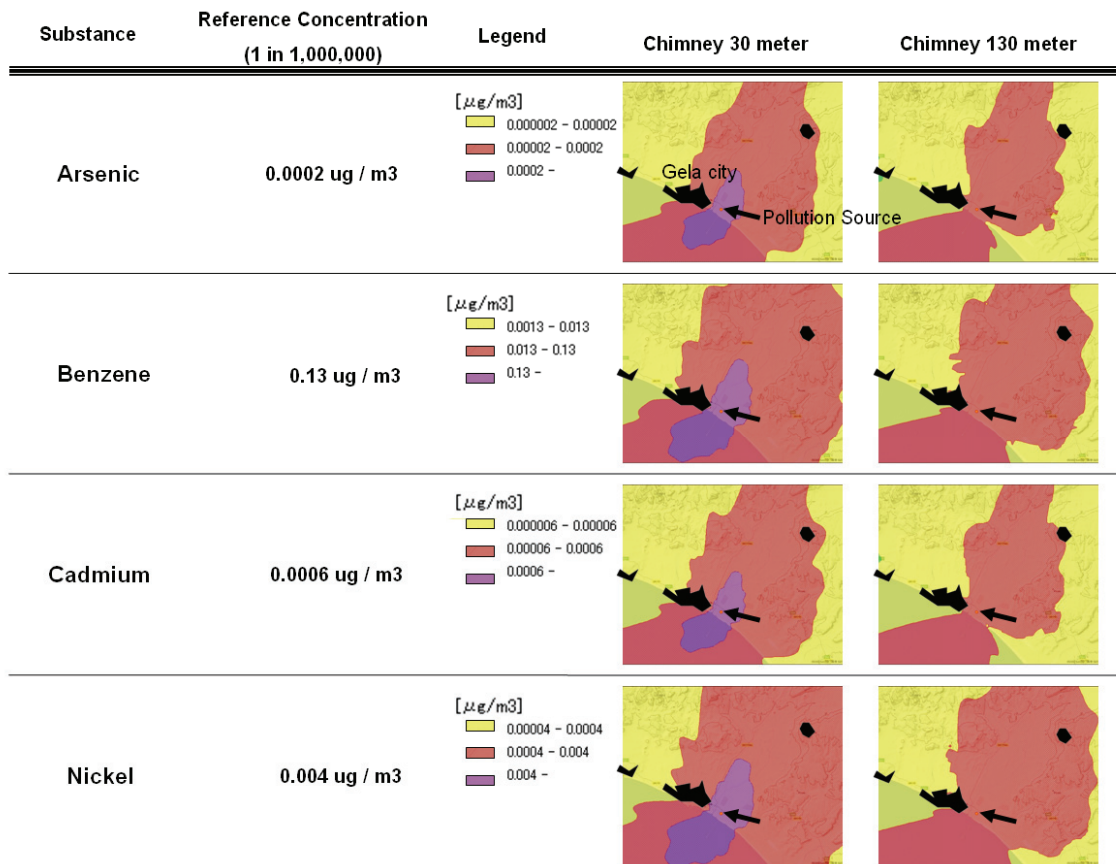


Figure 11. Concentration of As, Benzene, Cd and Ni, calculated by METI-LIS

## 6. Discussion

Through a case study in Gela we made clear three main points related to the IPPC Directive: access and use of public data, possible inconsistency of public environmental data, contextual area problems regarding air pollution and contamination surveillance in general.

We stressed that IPPC has a vertical integration perspective, in addition to more explicitly mentioned horizontal integration. This vertical integration is important to integrate actors and principles, different fields of work, production, emission, monitoring and impact data and to determine proper ELVs. Looking for a horizontal and vertical integration, several inconsistencies and missing data problems were found out. In particular the results from the LCA and the EPER registered emission data appear generally inconsistent. This inconsistency is related to some

particular pollutants such as CO<sub>2</sub>, SO<sub>x</sub> and Zn, while benzene and Ni correlate.

It is not possible to conclude which factor most contributes the data inconsistency only by looking at data, but it is an important first step to clarify these inconsistencies among data sources. In presence of data inconsistency, several factors have to be considered;

- Do data production present problems (e.g. errors in measures or sampling)?
- Are monitoring plans and methodologies proper to describe the situation?
- Who and in which way certifies the goodness of one data?
- Do actors who produce data have incentives to distort data?

The first point is usually linked to the fact that data are usually employed with few controls if not without any check.

Regarding the second point we can add some considerations. The elaboration of the LCA results gave some indications on critical aspects that have to be considered: V levels should be monitored with an environmental surveillance plan (emission, air, soil, etc.). The monitoring system is inadequate for some pollutants, e.g. Benzene concentration in the air is hourly monitored in only one station in Gela. In Gela, there is the lack of an environmental surveillance plan including biological monitoring for food (e.g. milk, fish etc.). Furthermore, there is not a plan of monitoring for the POP.

The third and fourth points are linked together. Regarding the last point some comments can be added. When an authority checks the emission from chimneys, an industrial operator can have an incentive to manipulate its declared emissions. Unlike other industrial typologies, the plants that constitute a refinery are not authorized with specific limits of emissions, but they have all together to respect an overall limit called bubble, that means to consider the refinery as a whole and to sum up concentrations and volumes of all the emission sources. To tackle this problem, using LCA to compare registered and directly measured emissions would reduce such incentive. Further, even when the registered data is not correct and the measured by the authority does not reflect regular emission activity by such distortion, using dispersion model to compare between the concentration of pollutant in media calculated by emission and directly measured concentration in monitoring stations demands more consistency in data and would further reduce the incentive of distorting data.

The case study run in Gela offers also some suggestions for further research. We organized a list of basic regarding integration in risk assessment, this check list, in particular the items that were not sufficiently answered (Tab. 3), represents the future direction for the more elaborated IPPC.

- Quantitative process data specific in Gela should be further investigated. So far, Ecoinvent

database is available, but further geographically and technologically specified data is favorable. IPPC Directive has a mechanism of exchange of information (EC, 2008a: Article 17). BREFs has fostered exchange of information among sites though it is not quantitatively enough to run LCA.

- Methods to be used for analysis on water and soil are to be specified. There exists dispersion model for water and soil, but they demand more data. The balance between available data and models has to be clarified.
- The stocks of pollutants in different media and targets in risk have to be considered, especially in the case of Gela. The data of the past emissions and quality of air, water and soil are scarce, thus we have to rely on the accumulation of pollutants at present to analyze cause-effect chain even by the activity of any industrial operator in the past.
- EPER's registered emissions are limited. V is not included in the 50 pollutants to be registered in EPER, though according to our LCA simulation V is relevant and should be considered in particular for human toxicity effects.
- A future complementary work should envisage the possibility of a Substance Flow Analysis (SFA) to further identify the main environmental impacts and the most polluting stages in the production processes generating persistent/bioaccumulative pollutants (e.g. PCDD/F, PCB dioxin-like, PAH, POPs).

## **7. Conclusions**

The main purpose of this work was to obtain the first picture of the environmental impacts associated to the presence of a large refinery in Gela, in Italy, using an LCA focusing on direct emissions from the territory. LCA allows to produce an integrated approach that can characterize the parameters defining the environmental behavior of a system, e.g. a refinery. This work has followed some of the key points related to the European Integrated Pollution Prevention and Control Bureau EIPPCB. Based on public available data the approach of the IPPC Directive was illustrated for the case of the refinery and petrochemical industry in Gela. In particular the LCA gave the opportunity to check the availability of environmental data from public accessible sites such as from the EIPPCB. This work shows some of the limits and possibilities of available public data. The application of the IPPC Directive in Italy, as in other countries (Barros et al. 2007), presents some problems due to the fact that the environmental competences were transferred by the Italian Government to the regions (Ministero dell'Ambiente e della Tutela del Territorio, 2005). Activity controls in the territory are organized on regional basis (run by the regional environmental agencies ARPAs), while the national authority is competent to grant the environmental permit to a given IPPC installation, establishing



previously the ELV (Emission Limit Value) based on BAT. Also notice that LCA is ordinarily utilized to analyze “cradle to grave” of products and their processes for Integrated Product Policy (IPP) for instance. Meanwhile, in this paper, LCA was applied in the context of IPPC Directive, where decisions shall be made on each territory rather than each product.

The process of integrating long chains of actions and effects is a very interesting social construction in which the scientific evidence, the industry interests, the legislation framework and the political debate have to meet and find a compromise or conflict. Participation can happen only in a regime of provision and circulation of reliable information to the public that can allow knowledge-based decisions. The democratization process can be improved only by a transparent production, collection and accessibility of data. This is the fundamental prerequisite (Aarhus Convention, 1998).

## 8. References

Aarhus Convention (1998) Aarhus Convention on Access to Information and Public Participation in Environmental Management

Bharti P., Henderson G.E., Haswell S.J., Grzes R. (1990) Speciation of vanadium present in a model yeast system. *Analyst*, 1990, 115, 1063 – 1066.

Bieñ J. D., Meer J. ter, Rulkens W. H., H. H. M. Rijnaarts (2005) *A GIS-based approach for the long-term prediction of human health risks at contaminated sites*. *Environmental Modeling and Assessment*, Volume 9, Number 4 / January, 2005, 221-226

Barros M.C., Bello P., Roca E., Casares J.J. (2006) Integrated pollution prevention and control for heavy ceramic industry in Galicia (NW Spain). *Journal of Hazardous Materials* 141 (2007) 680–692

Bosco M.L., D. Varrica, G. Dongarrà (2005) Case study: Inorganic pollutants associated with particulate matter from an area near a petrochemical plant. *Environmental Research* 99 (2005) 18–30

Canter L.W., Kamath J. (1995) Questionnaire Checklist for Cumulative Impacts. *Environ. Impact Assess Rev.* 1995; 15: 311-339

Colina M., Gardinerb P.H.E., Rivasc Z., Tronconec F. (2005) Determination of vanadium species in sediment, mussel and fish muscle tissue samples by liquid chromatography–inductively coupled

plasma-mass spectrometry. *Analytica Chimica Acta*, Vol. 538, Issues 1-2, 4 May 2005, Pages 107-115

EC (1996) Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control

EC (2000) Commission Decision 2000/479/EC  
[http://eper.ec.europa.eu/eper/documents/comission\\_17072000.pdf](http://eper.ec.europa.eu/eper/documents/comission_17072000.pdf) (04/11/2008)

EC (2004) Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. <http://eur-lex.europa.eu/>

EC (2008a) Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 Integrated pollution prevention and control

EC (2008b) The IPPC Directive: Towards a future policy on industrial emissions  
<http://ec.europa.eu/environment/ippc/index.htm> (25/03/2008)

EC (2008c) Directive on ambient air quality and cleaner air for Europe. Directive 2008/50/Ec of the European Parliament and of the Council of 21 May 2008

Ecoinvent (2005) Ecoinvent data, versjon 1.2., Swiss Centre for Life Cycle Inventories.

Eni divisione Refining & Marketing (2007) La Raffineria di Gela S.p.A., La Raffineria di Gela S.p.A., 5 giugno 2007.

EU (2006) Guidance document for the implementation of the European PRTR.

Guinée, J. (2002) Handbook on Life Cycle Assessment Operational Guide to the ISO Standards, 708p, Kluwer Academic Publishers.

Hellweger F.L., Wilson L.H., Naranjo E.M., Anid P.J. (2002) Adding Human Health Risk Analysis Tools to geographic Information Systems. *Transactions in GIS*, 2002, 6(4): 471-484.

Huijbregts, M.A.J., Thissen, U., Guinee, J.B., Jager, T., Van de Meent, D., Ragas, A.M.J., Wegener

Sleeswijk, A., Reijnders, L., 1999. Priority assessment of toxic substances in life cycle assessment. Part I: calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA. *Chemosphere* 41, 541-573.

Huijbregts, M.A.J., U. Thissen, T. Jager, D. van de Meent and A.M.J. Ragas, 2000. Priority assessment of toxic substances in LCA. II: Assessing parameter uncertainty and human variability in the calculation of toxicity potentials. *Chemosphere* 41: 575-588.

Italy (2005) DL.vo n.59 (18 February 2005)

Karstens S.A.M., Bots P.W.G., Slinger J.H. (2007) Spatial boundary choice and the views of different actors. *Environmental Impact Assessment Review* 27 (2007) 386–407

Manno E., D. Varrica, G. Dongarrà (2006) Metal distribution in road dust samples collected in an urban area close to a petrochemical plant at Gela, Sicily. *Atmospheric Environment* Volume 40, Issue 30, September 2006: 5929-5941

**Ministero dell'Ambiente** e della Tutela del Territorio **(1990)** *Istituzione aree ad alto rischio di crisi ambientale. Delibera* Ministero dell'ambiente e della Tutela del Territorio, 30 novembre **1990**.

**Ministero dell'Ambiente** e della Tutela del Territorio **(2000)** Perimetrazione del sito di interesse nazionale di Gela e Priolo. Decreto Ministero dell'Ambiente e della Tutela del Territorio, 10 gennaio 2000.

Ministero **dell'Ambiente** e della Tutela del Territorio (2005) Attuazione integrale della direttiva 96/61/CE relativa alla prevenzione e riduzione integrate dell'inquinamento. Decreto Legislativo 18 febbraio 2005, n.59

**Ministero dell'Ambiente** e della Tutela del Territorio **(2007)** Linee guida per le raffinerie sulla prevenzione e riduzione integrate dell'inquinamento. Decreto n.127 del Ministero dell'Ambiente e della Tutela del Territorio del 31 Maggio 2007.

Mirasgedis S., Hontou V., Georgopoulou E., Sarafidis Y., Gakis N., Lalas D.P., Loukatos A., Gargoulas N., Mentzis A., Economidis D., Triantafilopoulos T., Korizi K., Mavrotas G. (2008) Environmental damage costs from airborne pollution of industrial activities in the greater Athens,

Greece area and the resulting benefits from the introduction of BAT. *Environmental Impact Assessment Review* 28 (2008) 39–56

Paris I. (2007) I siti di interesse nazionale di Gela e Priolo: quadro ambientale e attività di bonifica  
Paper presented at the Conference Approcci Sostenibili per la Gestione e la Bonifica di Mega – Siti:  
Nuove Prospettive. Venezia 30 novembre 2007

US-EPA [www.epa.gov/](http://www.epa.gov/)

WHO (2006) *WHO air quality guidelines (AQG) - global update 2005*. Copenhagen: World Health Organization.

## **CHAPTER 4**

### **Is low carbon society embedding or embedded in economy?:**

#### **Speed on the constraint or liberation from it**

##### **Abstract**

The aim of this paper is to define Low Carbon Society (LCS) based on IPAT equation, starting from the problem definitions; 1) economy is not everything for low carbon society and 2) It is not clear if speed on the constraint is more important than liberation from it. To tackle these problems, two research questions are set; 1) what are the basic indicators, objects and constraints to shape the argument of Low Carbon Societies? And 2) What are the historical paths of several countries and what can be said for their future paths toward carbon societies? Time series data from 1900 or before is used while IPAT equation is used as the core methodology. In addition to IPAT variables, the importance of land per capita shall be considered as another basic indicator for LCS, related to the carrying capacity. The three different kinds of objects (i.e. total GDP, GDP per capita and social indicator) and the two constraints (i.e. total emission and emission per capita) are considered and it is shown that the combination of these objects and constraints strongly affects the argument on whether Low Carbon Technology is enough for LCS or other socio-economic aspects such as population is important. Among several cases, the case where GDP per capita is object and total emission is constraint is given attention most and requires the further research in the future.

## **1. INTRODUCTION: What is LCS and how to approach this in this paper**

What is Low Carbon Society (LCS)? One of the definitions of LCS is that made in NIES (2006). A Low Carbon Society; 1) takes actions that are compatible with the principle of sustainable development, ensuring that the development needs of all groups within society are met; 2) makes an equitable contribution towards the global efforts to stabilize atmospheric concentrations of carbon dioxide and other green house gases at a level that will avoid dangerous climate change through deep cuts in global emissions; 3) demonstrates high levels of energy efficiency and uses low-carbon energy sources and production technologies, and 4) adopts patterns of consumption and behavior that are consistent with low levels of GHG emissions.

Society can be defined in diverse ways; the sizes of economy and population, types of technologies they use, lifestyles of consumption and activity not related to economic activities, legal framework, political system, beliefs such as religions, (emotional) intelligence quotients, to name a few, some of which are measurable, the others not and some of them include subjective values (e.g. the more GDP, the better).

The main scope of this paper is to describe Low Carbon Society by using several numerical indicators based on IPAT equation where environmental impact (I) is calculated from Population (P), Affluence (A) and Technology (T)<sup>10</sup>. In this manner, the goal, achieving LCS, is rather mechanically translated into objects and constraints; the three objects (i.e. GDP, GDP per capita and non-economic indicator such as happiness index) and the two different types of constraints (i.e. emission and emission per capita). Each choice on objects and constraints of LCS results in each different argument and logic.

## **2. PROBLEM DEFINITIONS and RESEARCH QUESTIONS**

### **2.1. Problem 1: Economy is not everything for Low Carbon Society**

In Japan, the two scenarios toward Low Carbon Societies in 2050 were illustrated (Nishioka, 2008: NIES, 2008a: NIES 2008b); Scenario A as active, quick-changing, and technology oriented society and Scenario B as a calmer, slower, and nature oriented society. To connect the past, the present and the future, the historical data of GDP/capita, CO<sub>2</sub> emission/capita and population since 1950<sup>11</sup> and

---

<sup>10</sup> For history and academic discussion on IPAT equation, read Chertow (2001)

<sup>11</sup> Data from Gapminder (2009)

the results of the two future scenarios in 2050 are integrated in Figure 12. The two questions are worth considering from this figure.

The first question is about whether the object of Low Carbon Society is GDP or GDP/capita. As in Stern Review and the Green Golden Rule (Chichilnisky, 1995), GDP rather than GDP/capita has been the main object for discounted utilitarianism which is widely used approach by economists<sup>12</sup>. This tradition can go back to the underlying moral principle for legal and social reforms in the 18th century, proposed by Jeremy Bentham, *the greatest happiness for the greatest number*, where the happiness can be interpreted as GDP/capita and the number as population. In such economics, the surplus of an economy, included in GDP, is allocated between consumption and investment for capital goods to maximize the sum of the present values of the utilities, for instance.

Meanwhile, in Millennium Development Goals (MDGs), the indicators are more related to GDP/capita such as GDP growth per employed person, and the proportion of population below \$1 per day (United Nations, 2008); the economy of each individual rather than the aggregated national economy is the object. Human Development Index (HDI), as summary measure of human development, also adopts GDP per capita (UNDP, 2009)

Does Low Carbon Society have priority over GDP for the whole economy or over GDP per capita for each individual? This has not been answered explicitly in LCS research community, for instance in LCS-RNet (2009). The rationale to pursuit GDP per capita could be based on human development and happiness for each individual. Meanwhile, one rationale in the economic theories for setting GDP as object (to maximize) would be that our society behaves so within the current market system.

Some market mechanisms are discussed in climate change policies; carbon tax, international fund for technology transfer, etc. If market actually maximizes GDP rather than GDP per capita, and ideal carbon tax would internalize all the externalities, which is supposed to lead the society to the “optimal path”, then it might not necessarily guarantee the increase of GDP per capita even though this could be the social object, because maximizing GDP and GDP per are not always consistent to each other.

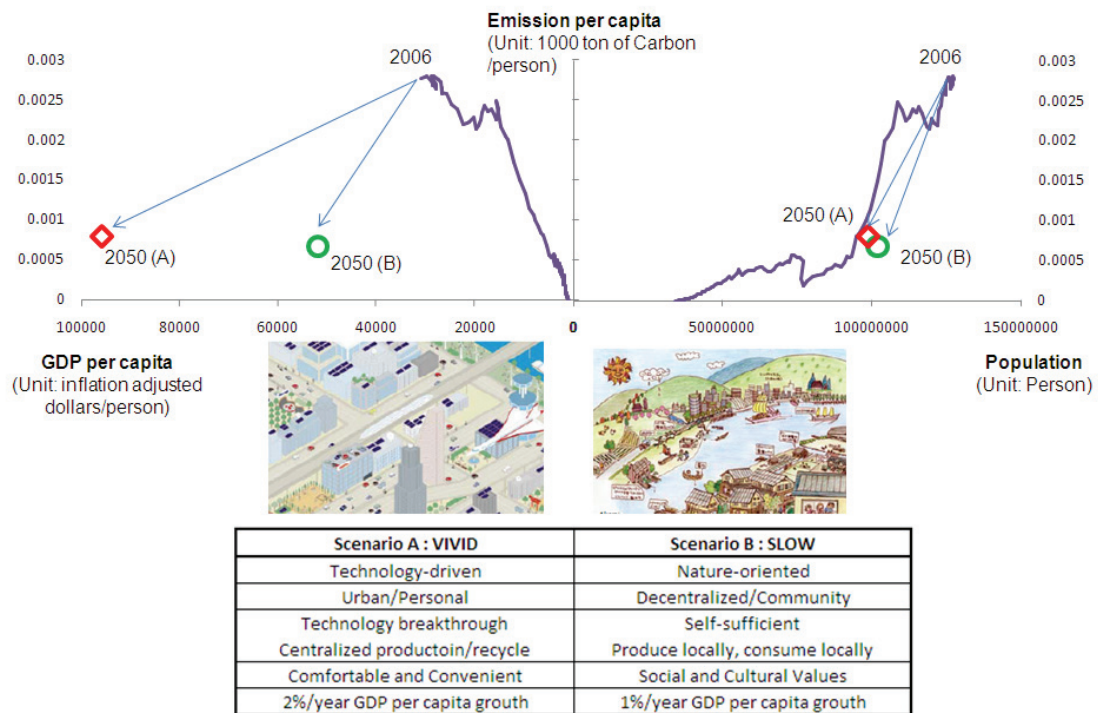
The second question is about whether the main object of Low Carbon Society can be measured by economic indicators such as GDP and GDP/capita. In Figure 12, Scenario A results in much higher GDP and GDP per capita than Scenario B, mainly because of the higher GDP growth rate. A society might prefer Scenario B, regardless of its lower GDP and GDP per capita. For instance, Karl Polanyi, in his book, *The Great Transformation*, pointed out three general types of

---

<sup>12</sup> Regarding the level of aggregation, Stern Review team (2007) wrote as follows; “Much of the discussion of values in this note and in the literature takes place at a high level of aggregation. Thus it considers total world consumption or income or aggregate country level income. There is often little distinction between different kinds of goods or allocation of individuals’ income across different periods of their lives. And in much of the formal modelling the attention to within country distribution is very limited”.

economic systems that existed before the society was embedded into free market economy: redistributive, reciprocity and householding. (Polanyi, 1944). Scenario B of Japanese low carbon scenarios is described as follows; “There would be many attractive local cities with original cultures and unique features. Citizens and NGOs play important roles in decision making processes.” The possible tensions between decision making processes between citizens and markets are also worth considering as seen in the one-sentence summary of *The Great Transformation*, by Kindleberger (1974); “Polanyi believed it outrageous that economic overwhelmed social considerations in the industrial revolution, but to prevent adaptation to market conditions may simply store up and aggregate the difficulties, as illustrated by the refusal of France to permit the modernization of agriculture from 1890 to 1950, leaving its peasants sodden, brutalized, inefficient, demoralized”.,

What are the indicators to properly illustrate Low Carbon Societies in addition to economic ones? This has not been answered yet.



**Figure 12. Historical path and future scenarios in Japan toward Low Carbon Societies in 2050<sup>13</sup>**

<sup>13</sup> GDP per capita in 2050 of Nishioka (2008) is converted into Purchasing Power Parity by the values in 2000 of Nishioka (2008) and Gapminder (2009).

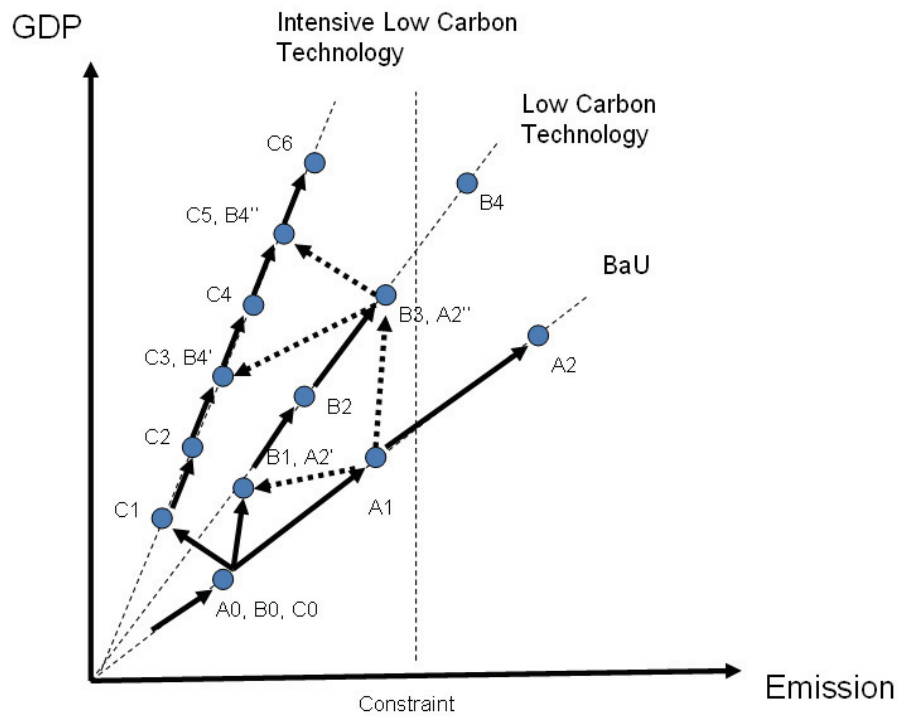


## 2.2. Problem 2: Speed on the Constraint or Liberation from it?

Low Carbon Society would have a constraint on total GHG emissions. In numerical modeling, the optimal solution is often found on the constraint, especially when the objects and constraints are assumed to be in trade-off relation. For instance, if the limit of GHG emissions is 50 giga ton of CO<sub>2</sub> equivalent, the optimal solution for the economic growth would be also when 50 giga ton is emitted. However, this depends on the assumptions. For instance, Figure 13 shows three paths (Business as Usual, Low Carbon Technology and Intensive Low Carbon Technology) and the constraint on emission, starting from  $t = 0$  (A0, B0 and C0). On the path of BaU, the economy cannot grow after  $t = 1$  (i.e. A1), since A2 is beyond the emission constraint. Thus, from A1, the economy has to make transition to the path with Low Carbon Technology. When  $t = 2$ , it can be in the same position of B1 (i.e. A2') or B3 (i.e. A2''). If the latter, is the case it can be said that taking the path closer to the constraint is more optimal, because it is quicker to arrive at the same location. However, if the former is the case, taking the path away from the constraint is faster for the rapid growth of GDP. When  $t = 1$ , if the speed of GDP growth is what to be maximized, A1 is better than B1 and C1. However, for the later periods, C1 might be the best; the direction away from the constraint is important especially when transition into more low carbon technology takes some cost.

In addition to the issue of the cost of transition, the assumptions on objects and constraints determine if trade-off would appear or not. For instance, the slope in the upper-left of Figure 17, later discussed, shows the trade-off between total GDP and total emission, while the slope in Figure 18 represents the trade-off between GDP per capita and Emission per capita. Thus, these two types of trade-offs do not directly mean neither the trade-off between total GDP and emission per capita nor that between GDP per capita and total emission. Thus, if the object is GDP per capita and the constraint is total emission, then the trade-off between them might not necessarily exist.

Will a Low Carbon Society be a society right on the threshold which does not violate the constraint, or a society liberated from such constraint? In this paper, the latter, the path to avoid the constraints, are further analyzed.



**Figure 13. Paths and constraint**

### 2.3. RESEARCH QUESTIONS

Considering these problem definitions, the following two research questions are derived.

- Research Question 1: Based on IPAT equation, what are the basic indicators, objects and constraints to shape the arguments of Low Carbon Societies?
- Research Question 2: What are the historical paths of several countries and what can be said for their future paths toward low carbon societies?

### 3. DATA and METHODOLOGIES

As for methodologies, IPAT equation is used to decompose the emission (i.e. environmental impact) into each variable (i.e. population, affluence and technology), while defining the object of the model (e.g. GDP, GDP per capita). IPAT is employed in this paper because each variable in IPAT equation is in scalar value so that several variables can be shown simultaneously in phase diagram and also

because the equation is very similar to the structure of Input Output Analysis and Life Cycle Assessment (LCA), which model the material balance in economy<sup>14</sup>.

Most of the data are obtained from Gapminder (2009), such as GDP/capita (in Purchasing Power Parity), CO2 emission per capita and population, since it has the consistent dataset covering many countries, many different types of economic, environmental and social indicators and long time series (e.g. from 18th century for GDP/capita). Especially preparing the data for longer time scale is important, because time scale would define the nature of argument.

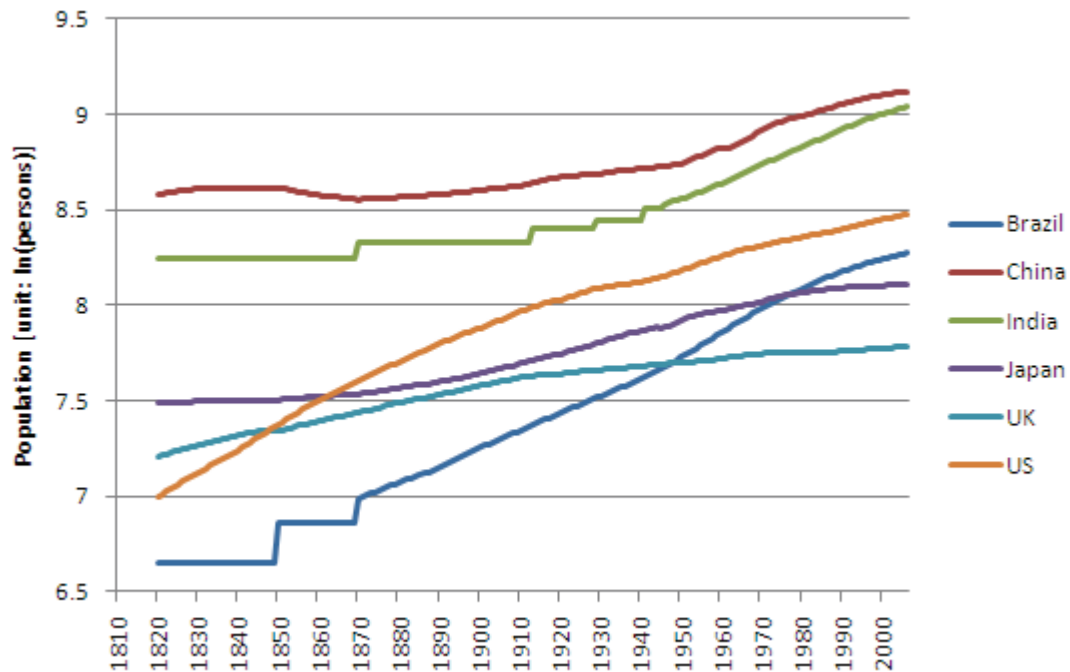
For instance, when one states in the beginning of 21th century, concerning climate change, “China is one of the most rapidly developing countries, where population and GDP per capita are growing in high rate, thus it might be that they are more responsible than people in other countries.”, what kind of time scope does he/she frame in mind, and by comparing to what are the numbers high or low? Contrarily to such view, an economist, Angus Maddison who has analyzed historical statistics of world economy, can show another perspective (Maddison, 1998).

Already in the tenth century, [China] was the world’s leading economy in terms of per capita income and this leadership lasted until the fifth century. It outperformed Europe in levels of technology, the intensity with which it used its natural resources, and capacity for administering a huge territorial empire. [...] In the nineteenth and first half of the twentieth century, China’s performance actually declined in a world where economic progress greatly accelerated.

As shown in this statement, “developing, developed, declining or declined” all depends on time scale. For instance, historical data on population is shown in Figure 14 (with logarithmic scale).

---

<sup>14</sup> For details about these similarities, see Heijungs (2001) and Heijungs and Suh(2002)



**Figure 14 Historical Population**

Following to our “common knowledge” in the end of 20th century, the rates of population growth in China and India are higher than those of US, UK and Japan. However, if we consider the whole 19th and 20th centuries, this is not the case. For example, that of US is much higher than that of China. And those of China and UK are similar to each other. This is also why setting long time frame is important to construct arguments. Notice that in logarithmic scale, the slope corresponds to growth rate.

## 4. ARGUMENTS and RESULTS

### 4.1. IPAT equation and Basic Indicators for LCS

As IPAT equation has been chosen as the core methodology to be used in this paper, first this equation is explained in this section. IPAT equation is described as follows<sup>15</sup>.

$$\begin{aligned} \text{total CO}_2\text{emission} &= \text{Population} \times \text{Affluence} \times \text{Technology intensity} \\ &= \text{population} \times \frac{\text{total GDP}}{\text{population}} \times \frac{\text{total CO}_2\text{emission}}{\text{total GDP}} \end{aligned}$$

<sup>15</sup> For details and variations of IPAT equation, see Chertow (2001)

These indicators in IPAT equation correspond to main variables in economic models such as General Equilibrium. The difference is that the indicators in IPAT are in scalar values, while variables in economic models are in vector and matrix as well as scalar. For instance, in a model of general economic equilibrium by Neumann (1945)<sup>16</sup>, technology is expressed in matrix (product by sector), production and consumption in vector (by sector), price in vector (by product), growth rate and interest rate in scalar which mathematically means a unique eigen value of the technology matrix.

Growth is not dealt properly in IPAT equation (thus in this paper), since it decomposes the impact into several variables. However notice that growth of economy is strongly related to surplus and how to use it. When an economic system can produce more than it needs to sustain its own system, it can either i) invest for future growth, ii) consume not for the purpose of growth (e.g. drinking festival), or iii) increase leisure for actors (e.g. people have more time for non-economic activity). How to use surplus is related to social vision as well as the assumptions of each model. Decomposition can be interpreted as the process of attributing responsibilities (i.e. GHG emissions) to several elements. When such decomposition deals with growth, it even decomposes growth of emission into each variable; mathematically it is described as totally differentiable as written below<sup>17</sup>:

$$dI = \frac{\partial I}{\partial P} dP + \frac{\partial I}{\partial A} dA + \frac{\partial I}{\partial T} dT$$

For instance, calculating multiplier effect of static Input Output Analysis follows similar logic. Meanwhile, in dynamic model such as Neumann (1945), growth cannot be decomposed into each variable, but be dealt with the concept of eigen value and vector.

In addition to these variables, land per capita would be important variable for considering Low Carbon Societies, partly because the visions of LCSs are strongly related to how they use lands as seen in the illustrations of two different scenarios in Figure 12, partly because land has been one of the principal elements among economists from the past, such as François Quesney who made *Tableau Économique* in 1759 and to the present such as ecological footprint, whose concept has been turned into carbon footprint in climate change arena, though the unit is not square kilometer anymore but ton-CO<sub>2</sub> eq. Also in LCS-RNet annual meeting in bologna in 2009, it was pointed out that

---

<sup>16</sup> Also in models of Input Output Analysis (IOA) and Life Cycle Assessment (LCA), technology is expressed by matrix and production level and final demand are defined by vector. Notice that these models do not consider monetary balance, thus there is no price vector. Also notice that they do not originally consider growth, since they are static models. For mathematical foundations of IOA and LCA, see Heijungs (2001) and Heijungs and Suh(2002).

<sup>17</sup> See Gans and Jöst (2005), for one example among many.

terrestrial policy is one of the key issues to achieve low carbon society (LCS-RNet, 2009).

Figure 15 shows territorial size of each country (unit: square kilometer) divided by population in arithmetical scale. Variation of quality of land (e.g. suitability for farming, living and extracting other natural resources) is not considered at all for simplification, but, solely from this figure, it could be possible to reason that the decrease of land/person is saturated in UK, India and Japan with current technology, China is getting close to it, while lands of Brazil and US have more capacity for population.

Regarding terrestrial size and policy, it is worth considering about “the optimal size”. Kindleberger (1974), in discussion off the tension between economic and social goals, suggested that the optimal size of economic space is the world, whereas the optimum size of society is small enough to allow each person to have a sense of participation. When we think about numerical indicators such as total population, total square kilometer of land in a nation or population density, we would assume that they can be summed, subtracted, multiplied, divided and averaged. However, if we consider the optimal size of society, we soon realize that this is not the case.

There is also another interesting aspect on this indicator, square kilometer per capita, in regard to the concept of carrying capacity, in contrast to the indicator for emissions. When we think about the carrying capacity of the climate against climate change, total anthropogenic emission, rather than emission per capita, could well define the capacity<sup>18</sup>, since emission itself is the harm for climate. Meanwhile, the carrying capacity of land stressed by people would be properly defined by land per capita, not by total available land, since people are the stressing factor for land.

---

<sup>18</sup> In this paper, both of the constraints, total emission and emission per capita, are taken into account, since there has been an argument that emission per capita is better indicator to allocate the responsibilities, while this is not directly connected to the carrying capacity.

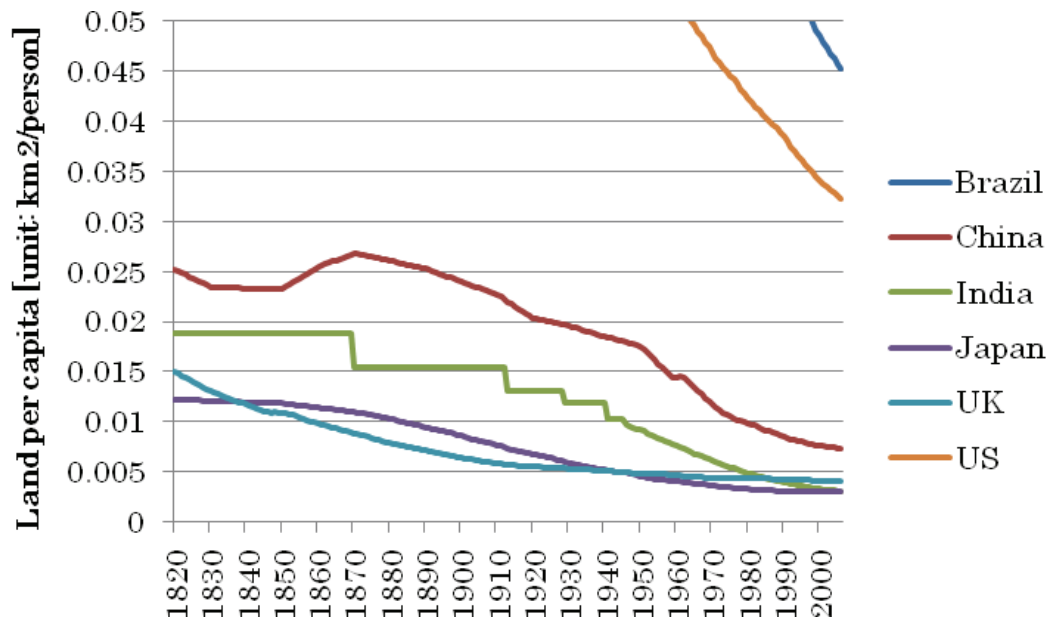


Figure 15. Historical Data of Land per capita

## 4.2. Framing Objects and Constraints

As already discussed in the first of problem definition, the three different kinds of objects are set for considering the paths for Low Carbon Societies; GDP, GDP per capita and indicators such as Human Development Index and Satisfaction with Life Index, which cover the aspects of human society more than economic ones (named Social Indicators<sup>19</sup>). For instance, a object of a society can be set as “achieving 20% of GDP per capita increase by 2050”.

As for the constraints, emission (e.g. unit: ton) and emission per capita are chosen. Indicator of land, square km per person, is important both as amenity (i.e. object) and constraint, but the further numerical analysis on this matter (land as constraint) is out of the scope of this paper.

How can one choose between the constraints; total emission and emission per capita? If the carrying capacity of GHG absorption in the environment is the start of the logic, one would choose total emission as the constraint. If he starts from the logic that GDP per capita shall be the same for any individual thus the constraint on emission shall be also based on per capita, then emission per capita would be proper. Meanwhile, this paper also will introduce a case where GDP

<sup>19</sup> These social indicators are also affected positively by GDP/capita, for instance, since HDI consists of life expectancy index, education index and the value calculated from GDP per capita. Thus social indicators do not mean that they exclude economic ones but rather that economic indicators are embedded in social ones.

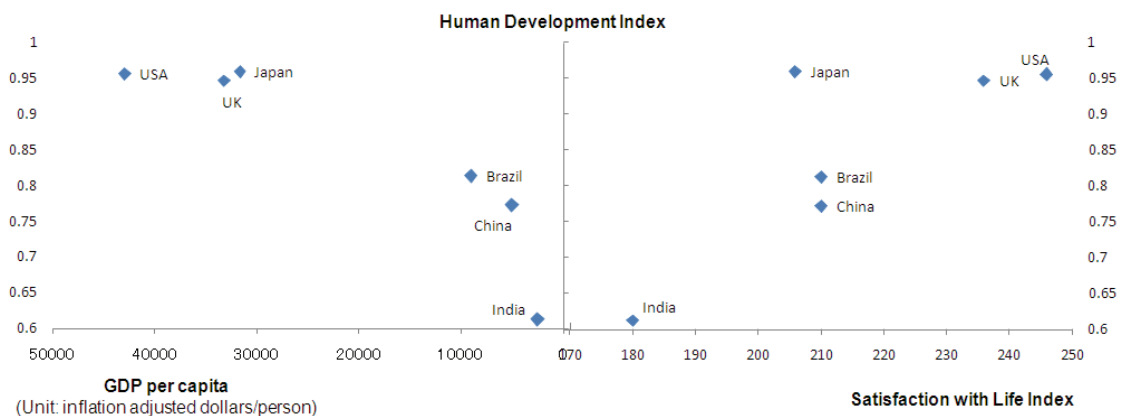
per capita is the object while total emission is the constraint (Case C in Table 3, discussed later).

Base on these objects and constraints, the five different cases are analyzed as illustrated in Table 3.

**Table 3. Five cases with different objects and constraints**

|        | OBJECT           | CONSTRAINT          | Low Carbon<br>TECH | OTHER VARIABLES       |
|--------|------------------|---------------------|--------------------|-----------------------|
| Case A | GDP              | Emission            | Yes                | Population            |
| Case B | GDP              | Emission per capita | Yes                | Population            |
| Case C | GDP per capita   | Emission            | Yes                | Population, Affluence |
| Case D | GDP per capita   | Emission per capita | Yes                | Population, Affluence |
| Case E | Social indicator | -                   | -                  | -                     |

For Case E, the biographical path of population, affluence, technology and impact is not analyzed and discussed, but it is shown in Figure 16 that the correlation between GDP per capita and social indicators is not clear with samples of several countries around in 2007. This paper does not argue whether such social indicators are proper to measure human development or satisfaction with life, but indicates that there would be a possibility that such social goals are not necessarily achieved by increasing GDP and GDP/capita. As shown in Figure 12, visions toward low carbon societies would not be depicted solely by economic indicators. While taking into account of this case with the limitation of economic indicators to illustrate low carbon societies, Case A-D will be further analyzed in the following sections, by setting the objects of societies as GDP or GDP per capita.



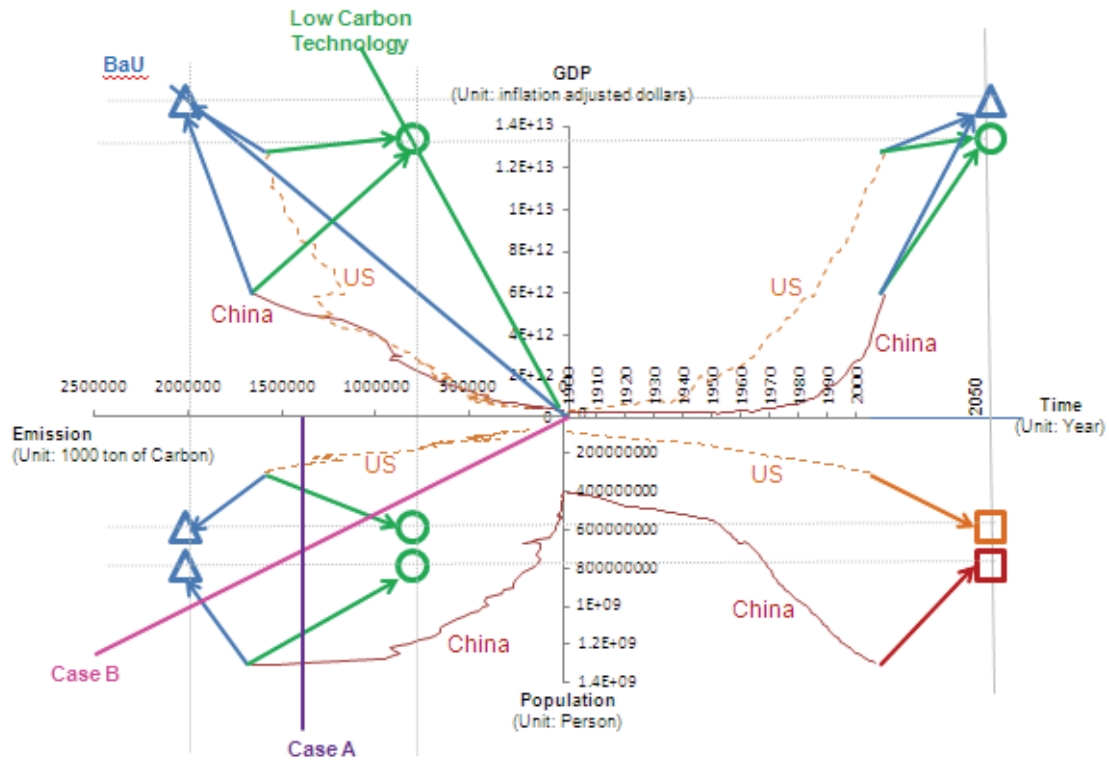
**Figure 16. Correlation between GDP/capita and social indicators<sup>20</sup>**

<sup>20</sup> GDP per capita (PPP) comes from Gapminder (2009) for the year 2007, Human Development Index comes from UNDP (2009) for 2007, and Satisfaction with Life index from White (2007) for 2006.



### 4.3. Historical and Future Paths toward LCS

For an example, paths for China and USA are shown. First, Case A and B are analyzed and discussed in Figure 17.



**Figure 17. GDP is Object for society (Case A and B)**

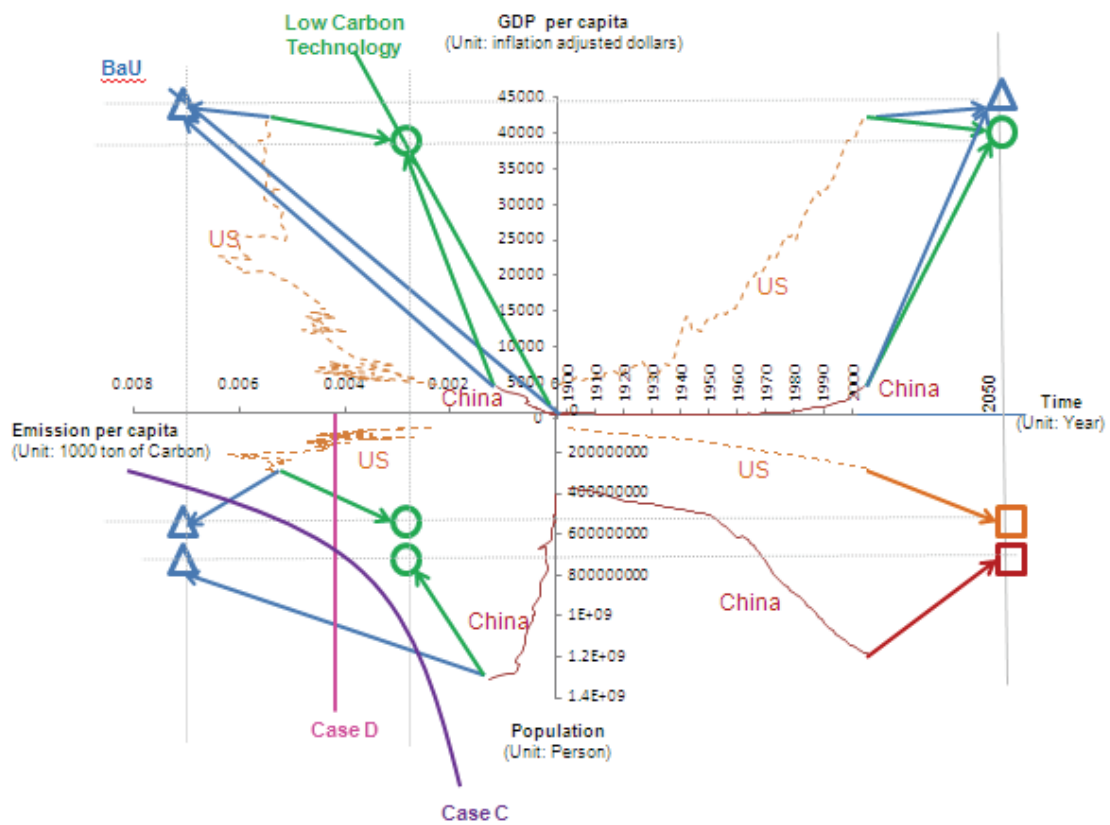
The path of each country is drawn for the past (1900-2006) and for the future (to 2050). Targets of GDP and population in 2050 are on the right side of the figure. The efficiency of technology is given by the slope in the upper left part. In the bottom left part of the figure, the constraint of emission is parallel to y-axis (for Case A), while that of emission per capita is the slope (for Case B).

This behavior of this figure is based on the assumption that GDP and technology affect total emission, not population, since GDP itself is given exogenously regardless of population. This can be expressed by changing IPAT equation into  $I = GDP * Technology$  because  $Population * Affluence = GDP$ . Population is not directly affecting the economy in this framing. For some economists, such as Thomas Robert Malthus, land and population are the main drivers of economy system. Meanwhile, the original basic variables of Input Output Analysis by Wassily Leontief solely consist of final demand (e.g. GDP) and technology, resulting into total output. Factor

inputs such as numbers of labours required are given endogenously, not exogenously affecting the economy.

This could lead to a strange conclusion for the constraint of emission per capita (Case B); if other things (e.g. GDP and technology) are the same, the more population, the less emission per capita.

For the constraint of emission (Case A), when the target of GDP is set, technology is the only variable that can be adjustable to meet the object; population does not affect the situation. From this logic, it can be said that Low Carbon Society can be achieved by Low Carbon Technology and the target of GDP, not by other socio-economic elements such as population and affluence.



**Figure 18. GDP per capita is Object (Case C and D)**

Targets of GDP per capita and population in 2050 are on the right side of the figure. The efficiency of technology is given by the slope in the upper left part. In the bottom left part of the figure, the constraint of emission is the curve ( $A \cdot P < \text{constraint}$ ) (for Case C), while that of emission per capita is parallel to y-axis (for Case D). When GDP per capita, not GDP is set as target, the situation is different from case A and B. For the constraint of emission (Case C), not only technology but also

population are the elements to be adjusted to achieve the targeted affluence. Meanwhile, for the constraint of emission per capita (Case D), only technology affects whether the constraint is satisfied or not.

The outcomes of the logics for these four cases are summarized in Table 4.

It is important to notice that the strategies toward population changes very widely based on the assumption on object and constraint. These results suggest that not only GDP and technology but also socio-economic indicators such as affluence and population shall be properly integrated in consistent visions and strategies toward Low Carbon Society.

From the view that the carrying capacity of the environment is well expressed in total emission which shall be the constraint, Case A and C are feasible, while Case B and D focus on the equity of responsibility.

From the assumption that economy behaves to maximize GDP regardless of visions toward low carbon societies, Case A and B are feasible, while Case C and D considers more on individual rather than the economy as a whole. GDP per capita can be also interpreted into the human rights to develop.

From the notion that trade-offs which might arise from the efficiency of technology shall be disappeared in objects and constraints, Case B and C are feasible, since population can be increased or decreased to get liberated from the constraint. Meanwhile, if somebody thought that standing right on constraints are the mother of efforts, development and progress, then Case A and D would be better.

From the logic that the carrying capacity of land is limited and less population is better, then Case B is not proper.

Thus, for instance, Case C satisfies the principles of the carrying capacity of the climate and land, human rights to develop and independence from trade-offs and constraints, but not necessarily the nature of the free market to maximize GDP.

**Table 4. Strategies of Technology and Population for each different object and constraint**

|        | <b>OBJECT</b>  | <b>CONSTRAINT</b>   | <b>Technology</b> | <b>Population</b>        |
|--------|----------------|---------------------|-------------------|--------------------------|
| Case A | GDP            | Emission            | More efficient    | Not Affecting the Object |
| Case B | GDP            | Emission per capita | More efficient    | More Population          |
| Case C | GDP per capita | Emission            | More efficient    | Less Population          |
| Case D | GDP per capita | Emission per capita | More efficient    | Not Affecting the Object |

## 5. CONCLUSION and DISCUSSION

Research questions have been answered as follows.

Research Question 1: Based on IPAT equation, what are the basic indicators, objects and constraints to shape the arguments of Low Carbon Societies? Answer: The indicator, land per capita, is another important indicator for Low Carbon Society. Notice that the carrying capacity of the environment against climate change can be properly expressed by total GHG emission rather than emission per capita, while the carrying capacity of land by land per capita. For object, social indicators such as Human Development Index and Satisfaction with Life index are worth being considered in addition to GDP and GDP per capita. In fact, setting objects for Low Carbon Society would be much complicated task, if we consider the simple facts that society consists of many people and that even the definition of human itself never has been converged; not only *homo sapiens as economic man*, but also *homo loquens*, *homo socialis*, *homo ludens*, *homo aestheticus*, *homo religious*, *homo ridens*, *homo demens* etc. For constraint, the rationale of constraint on emission (ton) and emission per capita (ton/capita) shall be given consistent logic between them. Also it is worth considering about if the optimal solution toward Low Carbon Society can be found on the constraint or away from such constraint.

Research Question 2: What are the historical paths of several countries and what can be said for their future paths toward low carbon societies? Answer: Not only GDP and technology but also socio-economic indicators such as affluence and population shall be properly integrated in consistent visions and strategies toward Low Carbon Society.

The two problems were defined in this paper; 1) Economy is not everything for Low Carbon Society and 2) Speed on the Constraint or Liberation from it? These problem definitions were not solved fully in this paper. However, the research questions and answers lead to the starting point for the discussion on these problems. Especially, the case C where the object is GDP per capita, the constraint is total emission and the population is going to decrease is interesting setting for the future research, since this assumption does not seem to contradict to the one of the definitions of Low Carbon Society cited in the beginning of the paper. The challenge of such society would exist in how to balance between social object (i.e. GDP per capita), nature of market to maximize total GDP, environmental carrying capacity of the climate and land (i.e. total emission and square kilometer per capita) and human population.

## 6. REFERENCES

- Chichilnisky, G., G. Heal, and A. Beltratti (1995), "The Green Golden Rule," *Economic Letters* 49: 175-179.
- Chertow, M. R. (2001) The IPAT Equation and Its Variants; Changing Views of Technology and Environmental Impact, *Journal of Industrial Ecology*, 4.4:13-29.
- Gans, O. and F. Jöst (2005) Decomposing the Impact of Population Growth on Environmental Deterioration, University of Heidelberg, Department of Economics, Discussion Paper Series No. 422.
- Gapminder (2009) Gapminder Documentation 001 – version 5, GDP per capita by Purchasing Power Parities.  
<http://www.gapminder.org/wp-content/uploads/2008/10/gapdata001-1.xlsx>  
(accessed on 2009/10/01)
- Heijungs, R. (2001) *A theory of the Environment and Economic Systems: a unified framework for ecological economic analysis and decision-support*, Edward Elgar Publishing, Inc.
- Heijungs, R. and S. Suh (2002) *The computational structure of life cycle assessment*, Kluwer Academic Publisher.
- Kindleberger, P. (1974) The Great Transition by Karl Polanyi, *Daedalus*, Vol. 103, No.1, Winter 1974, pp.45-52.
- Maddison, A. (1998) Chinese economic performance in the long run, OECD Paris.
- Nishioka, S. (Editor) (2008) *Japan Low Carbon Society Scenarios –the path for 70% reduction of CO<sub>2</sub>-*, Nikkan Kogyo Shinbun.
- Polanyi, K (1944) *The Great Transformation*, Beacon Press.
- LCS-RNet (2009). Achieving a Low Carbon Society - Synthesis Report: Inaugural Meeting of the LCS-RNet (International Research Network for Low Carbon Societies).

National Institute for Environmental Studies (NIES), Kyoto University, Ritsumeikan University and Mizuho Information and Research Institute (2008a) Japan Scenarios and Actions towards Low-Carbon Societies (LCSs).

National Institute for Environmental Studies (NIES), Kyoto University, Ritsumeikan University and Mizuho Information and Research Institute (2008b) a Dozen of Actions towards Low-Carbon Societies (LCSs).

Stern Review team (2007) Value judgements, welfare weights and discounting: issues and evidence. [http://www.hm-treasury.gov.uk/media/D/B/stern\\_yaleb091107.pdf](http://www.hm-treasury.gov.uk/media/D/B/stern_yaleb091107.pdf)

United Nations (2008) The Millennium Development Goals Report

UNDP (2009) Human Development Report 2009, Overcoming barriers: Human mobility and development.

Von Neumann, J. (1945) A Model of General Economic Equilibrium, *Review of Economic Studies*, 13:1-9.

White, A (2007) A Global Projection of Subjective Well-being: A Challenge To Positive Psychology? *Psychtalk* 56, 17-20.

# CHAPTER 5

## General Discussion and Conclusions:

### Answers to meta-research questions in relation to meta-framework

#### 1. Answers to Meta-Research Questions and Discussion

Starting from the theme of the thesis, ‘finding innovative solutions to complicated environmental problems’ (ISIE, 2009), and the scientific approach (i.e. the three models and the three analytical techniques), the three meta-research questions are posed in Chapter 1, each of which is discussed in Chapters 2-4 with specific questions designed to provide solutions for each case. This last synthesis chapter summarizes the results, provides answers to the meta-questions and concludes the overall discussions.

Chapter 2 is titled, *Static life cycle assessment with external demand and the dynamic Leontief model with growth: Two different engines in consumption and production systems*. This chapter first reviews static tools of industrial ecology such as the IPAT equation and inventory analysis of life cycle assessment (i.e. LCI) whose logic starts from fixed consumption. The ‘reverse’ use of LCI from decomposition analysis for analyzing contributions of each exogenous variable to environmental impacts to marginal analysis for foreseeing impacts by changes in the variables is identified. Then the dynamic Leontief model is contrasted to LCI to clarify the growth mechanism which has been missing in the static tools. Effects on environmental impacts by changes in external demand and technology efficiency are mathematically and computationally compared between the static and dynamic models. It is shown that the driver for energy and material flows in the static LCI model is external demand in a consumption system while the driver for the dynamic Leontief model is through a mechanism for generating a surplus allocated between consumption and investment for growth in a production system. Further discussions are made on sustainable consumption and production based on the outcomes and literature reviews in the field.

The meta-research question for this chapter is: *Do decomposition and attribution analyses explain cause and effect for the future?* The answer is:

*Answer 1:* Attribution analysis does not include the rebound effect. Decomposition and attribution analyses can be applied to static LCI, not to the dynamic Leontief model. In marginal analyses, the static and dynamic models would behave in different manners. Thus, it cannot be

concluded that decomposition and attribution analyses explain cause and effect for the future.

It is important to consider how the two different types of drivers which make material and energy flow in a system are explained by the two models: 1) external demand in a consumption system and 2) a mechanism for generating surplus in a production system in which the surplus is allocated between consumption and investment into economic capitals for growth or other uses (e.g. environmental and social capitals).

Arguments on strong and weak sustainability (see, for instance, Ayres (1998)) would give another insight to this surplus-generating mechanism since whether investing in environmental capital is feasible and whether economic capital and environmental capital are interchangeable or not would frame the core of discussions on growth and capital. In the context of sustainable consumption and production, the contrasts between the two drivers shall be simultaneously taken into account, especially when 'de-growth' (i.e. less economic consumption and production) is discussed (see Huppes et al. (2009) for further discussion on de-growth).

When capital investment by government (not consumption by households), which is part of external demand, increases in static input-output analysis (IOA)<sup>21</sup>/LCI, economic growth is foreseen in the model (i.e. more production led by more external demands). This outcome is also the same in the dynamic Leontief model; when investment increases there will be more growth in production in the future. In this case, the behaviours of the two systems are consistent with each other: when investment increases, economic growth can be achieved. The distinction between static and dynamic models might not be so important. The contradictory behaviours between the static and dynamic models as discussed in Chapter 2 have not been thoroughly discussed in other literature since IOA and the dynamic Leontief model were originally designed to analyze how to achieve more economic growth rather than de-growth. Meanwhile, in the discussions on de-growth, what matters is a decrease in consumption. When consumption decreases, production also decreases in IOA/LCI while production would by contrast grow in the dynamic Leontief model.

Chapter 3 is titled, *Industrial pollution in a petrochemical area, data accessibility and elaboration from a public perspective: A case study in Gela, Sicily*. The aim of this chapter is to consider which type of information can be retrieved from public databases to evaluate industrial pollution. This work illustrates the case of the petrochemical industrial site in Gela (Sicily, Italy) where there are several activities subject to the Directive on Integrated Pollution Prevention and Control (IPPC Directive). This chapter analyses the characteristics of this directive and defines the methodological issues related to implementing the IPPC Directive in a real case study. LCA and air pollution modelling was carried out using public data from the European Pollutant Emission Register (EPER)

---

<sup>21</sup> LCA is mathematically equivalent to static IOA (Heijungs and Suh, 2002).



and other sources in order to show the possibilities and limitations of accessing and using publicly available data. What is also addressed is the issue of integration of different data, scales and methodologies that are at the core of the development of any analysis of the impacts of industrial activities on environment and health.

The meta-research question for this chapter is: *Can attribution analyses investigate data uncertainty and supplement a lack of data for the cases whose causes took place in the past?* The answer is

*Answer 2:* With the support of a general technology database which contains coefficients of technology, emissions and impact, attribution analysis can clarify which data is uncertain and deficient and to what degree this uncertain/deficient data affects the results and shall be improved.

The analysis focuses on uncertain and deficient data for the present and the past, but such research also has important messages and possible effects for the future. The existence of general technology databases that are publicly available (i.e. have public access) and free of charge might transfer the ‘burden of proof’ for environmental impacts from the actors who receive the effects to those who are responsible for the causes. EC (2000) mentions ‘[w]here there is no prior authorisation procedure, it may be up to the user or to public authorities to demonstrate the nature of a danger and the level of risk of a product or process. In such cases, a specific precautionary measure might be taken to place the burden of proof upon the producer, manufacturer or importer, but this cannot be made a general rule’.

Without any data, the people who suffer from damages would have to prove why it happened while such data might be owned by the producers and therefore very difficult to access. With a general database, they can calculate the possible impact and ask producers, ‘Based on general data, this part of responsibility is attributed to your activity. If you disagree, please prove that your responsibility is less by disclosing your data’. This shift does not necessarily hamper activities of producers. Furthermore, ‘people’ are both consumers and producers living in the same society since consumers are also labourers and shareholders at the same time. The Pollution Release and Transfer Register (PRTR) regulation together with best available techniques would help such a transition, but relating process data with emission data (i.e. how much of X is emitted from the process by producing 1 kg of product Y) is still missing. This information would greatly help consumers and producers design sustainable consumption and production systems together. A publicly available database such as the Eco-Invent database already exists, but its data quality shall be improved and it is not free of charge. There is currently not enough public investment to construct such a database.

Chapter 4 is titled, *Is low carbon society embedding or embedded in economy?: speed on the constraint or liberation from it.* The aim of this chapter is to define a low-carbon society (LCS)

based on the phase diagram with the variables from IPAT (environmental impact,  $i$ , equals the product of population,  $p$ , affluence,  $a$ , and technology,  $t$ ), starting from the problem definitions: (1) Economy is not everything for LCS and (2) It is not clear if speed on the constraint is more important than liberation from it. To tackle these problems, two research questions are established: (1) What are the basic indicators, objects, and constraints for shaping the argument of LCSs? and (2) What are the historical paths of several countries and what can be said for their future paths toward a LCS? The phase diagram with the variables from the IPAT equation is used as the core methodology with time series data from 1900 or before while the importance of land per capita shall be considered as another basic indicator related to the carrying capacity for a LCS. The three different kinds of objects (i.e. total gross domestic product (GDP), GDP per capita, and a social indicator) and the two constraints (i.e. total emissions and emissions per capita) are considered. It is shown that the combination of these objects and constraints strongly affects the argument of the carrying capacity of climate and land, development of an economic system (based on GDP) and economic man (based on GDP per capita), and other human developments (possibly measured by social indicators). Among the four cases analyzed in the phase diagram, the case in which GDP per capita is objective and total emissions are a constraint is given the most attention and requires the most research in the future since it does not contradict the definition of a LCS. It is also suggested that if changing the direction of the green growth path with low-carbon technology development takes time and money, institutional arrangements would be necessary in addition to market mechanisms which just find optimal solutions under the constraints.

The meta-research question for this chapter is: *How are objectives and constraints established and what shall be the paths (e.g. speed or direction)?* The answer is:

*Answer 3:* Consistency between basic indicators of models and those of objectives and constraints would help to derive solutions. However, the latter is not necessarily the same as the former. For instance, even though GDP would be maximized in an economic model (supposedly this is the nature of an economic system), it might be desirable for society to set GDP per capita as its objective. In addition to this, in economic models, optimal paths are often found exactly on the constraints. However, considering that it would take time and money to divert a certain direction of growth to the other, it is worth considering the degree to which the path is diverted from the constraints; the direction of green growth would be more important than speed of economic growth.

In numerical models, paths are often endogenously calculated by optimization with exogenous data and what is optimized is the amount (whose derivation is its change, thus 'speed') rather than the direction of the path. For instance, just 'utility' or the more complicated 'present discounted utility' is maximized by CGE and the Hamiltonian. Meanwhile, the following equation is derived in Chapter

2:

$$\Delta \tilde{q} = \Delta \tilde{q}_{time} + \Delta \tilde{q}_f + \Delta \tilde{q}_T = C^{-1}(T_{out} \tilde{q}_{(t)} - T_{in} \tilde{q}_{(t)} - \tilde{f}) - C^{-1} \Delta T_{in} \tilde{q}_{(t)} - C^{-1} \Delta \tilde{f}$$

While models (or market mechanisms) would behave to maximize the ‘speed’ of economic growth (i.e.  $\Delta \tilde{q}$ ) under trade-offs between consumption and environmental emissions, society could decide on a ‘direction’ and take initiatives within the system by changing technology and consumption patterns (i.e.  $\Delta T_{in}$  and  $\Delta \tilde{f}$ ) while finding and applying social values to such changes and directing the path of green growth.

If ‘weak sustainability’ holds true where ecological and economic/social capital can be interchanged, priority might be given to speed. However, if ‘strong sustainability’ is needed, minimum amounts of a number of different types of capital (economic, ecological, and social) should be independently maintained in real physical/biological terms (Ayer et al., 1998). Thus, running on the edges of ecological constraints might not be a desirable situation; the direction providing liberation from the environmental constraints would be more important than the speed.

The issues on multiple objectives are also worth discussing. When a single actor integrates multiple indicators, it is often the issue of weighing between indicators—he can subjectively set the weights. Meanwhile, when multiple actors are involved, such weighting procedures shall be based on mutual consensus. Especially when considering the case of global commons, subjective preference for each individual might not be coordinated and adjusted through market or other platforms.

Regarding interactions with ‘platforms’, this thesis does not claim that market mechanisms are everything. According to Kenneth Boulding, who wrote ‘The Economics of the Coming Spaceship Earth’, there are three types of interactions between countries, individuals and any type of sub-system. The first is by destructive power based on a threat, ‘*Do something good to me, or I do something bad to you*’; the second by productive power based on exchange, ‘*If you do something good to me, I do something good to you*’ (close to market mechanism); and the third by integrative power based on something other than threat or exchange, ‘*I do as you want to do*’ (Boulding, 1989). Facing economic challenges and opportunities for growth, societies have had a history of fighting, marketing, integrating and separating with other societies. The climate change issue is not only about economic issues such as growth of GDP but also about energy-related national security and how to tackle this global problem in an integrative manner.

## 2. Overall Discussion in Meta-Framework

In summary, the following general messages are derived through the research questions and the answers:

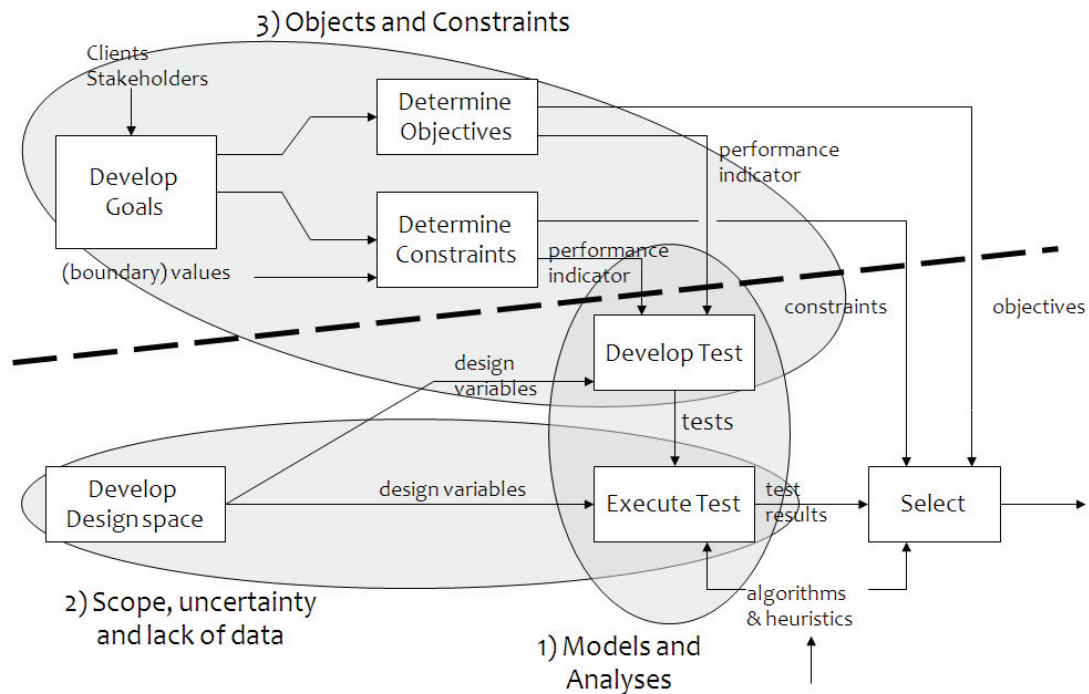
The difference in behaviour between static and dynamic models shall be considered for testing the feasibility of sustainable consumption and production (possibly towards de-growth if this is the social goal).

Scope, uncertainty of data and lack of data have to be properly taken into account and can be supplemented with general database information by technology. And such a database itself would suggest the scope to be covered (i.e. design space).

It is important to set objectives and constraints that are consistent with but separate from the basic variables of the models so that whoever has a goal can control the systems and not be controlled by the systems.

Figure 1 is a meta-design for a plan 'to bring the system into being' and support transition management. Developed in Delft University, the main steps are: i) the development of goals, objectives and constraints, ii) specifying the design space, iii) the development of tests and iv) setting up the tests in such a way that by executing the tests the best performing design can be selected for implementation (Chappin et al., 2008).

In Figure 1, the three messages are interrelated to these four points: 1) which logic and model to choose (e.g. static/dynamic) determines the behaviours of the basic design variables (for iii); 2) before running models, proper scoping of analysis and data are required (for ii); 3) social targets as performance indicators (e.g. total GDP or GDP per capita) have to be consistent with the variables that are to be maximized/minimized in the model (for i); and 4) all of these aspects shall be coordinated to enable proper decision making for selection (for iv).



**Figure 1. Meta-model for design (Chappin et al, 2008) and the four main topics of the thesis.**

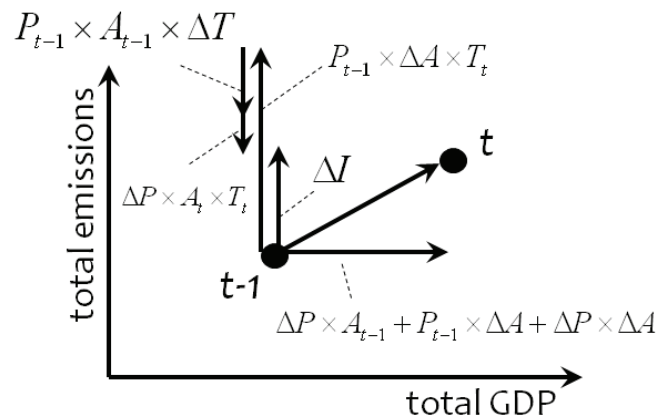
Each chapter of the thesis focuses on a different issue (i.e. behaviours of static/dynamic models, integrated environmental risk assessment, and a low-carbon society). Thus, generalizing might omit some important specific aspects. However, Figure 1 shows that testing with models and analyses links the two parallel processes for the meta-model for design: developing goals and determining objectives and constraints with performance indicators (upper part of the figure) and developing design space which defines the scope, clarifies uncertain data and a lack of data and derives design variables (lower part).

Thus, for ‘finding innovative solutions to complicated environmental problems’ (ISIE, 2009), it is worth developing overviews of what types of models and analytical techniques exist and what features are common/different as summarized in Table 2 of Chapter 1. Choosing which model to use determines which assumptions to accept. There is no objective rule for this, and it might be that a community that shares common goals, objectives and constraints subjectively tends to use a certain model/analytical technique; this may also be true for a community that shares common data. How to frame problems and which model/analytical technique to use is strongly affected by the goal and/or the data. If so, it would be very useful to consider the limits of each model/analytical technique and the challenges that must be overcome to find innovative solutions as demonstrated in Section 2 in

Chapter 1 and in Chapter 2 since expanding the boundary of a model/analytical technique could also expand the boundary of the goal (Chapter 4) and the data (Chapter 3). And innovatively discussing the goal and the data could also result in the development of a model/analytical technique as shown in Chapters 3 and 4.

This thesis started arguments with the three models (i.e. the IPAT equation, LCI and the dynamic Leontief model) and the three analytical techniques (i.e. decomposition, attribution and marginal analyses). Through the three meta-research questions as well as their specific-questions, the limits of these models and analyses and their corresponding challenges have been presented and discussed. How each model could contribute to innovatively scoping the goal and data is summarized as follows.

The IPAT equation is suitable for analyzing historical trends in population, GDP and emissions in a consistent logic so that the change in emissions can be explained by the changes in population, affluence and technology (i.e. decomposition analysis). Compared to static LCI and the dynamic Leontief model, it is less data-demanding and the coverage of countries and years can be much broader. Marginal analysis cannot be applied to this equation, but by expressing IPAT indicators in phase diagrams, IPAT can be used to deal with different types of objectives and constraints as shown in Chapter. 4. In addition to this, the results of decomposition analysis (eq. 2 in Chapter. 1) can be vectorized and shown in a phase diagram together with the trends of indicators (see Figure 2), which would be a great help when discussing the direction of green pathway growth.



**Figure 2. Vectorization of decomposition analysis and trends of indicators in phase diagram.**

LCI is a very useful methodology in the sense that decomposition, attribution and marginal analyses can be applied to it. It is more data-intensive compared to the IPAT equation. However, because of this characteristic, it would clarify scope, data uncertainty and lack of data for attribution analysis, especially combined with general databases of technology as shown in Chapter 3. As for marginal analysis, the difference in behaviours between LCI and the dynamic Leontief model have been

recognized as discussed in Chapter 2. For instance, less consumption leads to less emissions in static LCI (see eq. 4 in Chapter 1) but leads to more production and emissions in the future (see eq. 8 in Chapter 1).

The dynamic Leontief model includes an endogenous growth mechanism; change in production between times  $t$  and  $t+1$  depends on the production level at time  $t$ . By contrast, in static LCI production level does not change unless the exogenous variables change. This mechanism of surplus endogenously derived from the economic system itself, allocated to consumption and investment, shall be considered further in research on sustainable consumption and production. How to set goals, objectives and constraints with performance indicators in the context of sustainable consumption and production remains a challenge for society. In addition to this, concrete data on capital and corresponding depreciation periods are very difficult to define and obtain, and the disaggregation level of industries is much lower in the dynamic Leontief model compared to static IOA/LCI. We have to be careful about this so that data availability shall not be a bias for which logic and model to choose.

As discussed above, in an opposite manner, innovatively discussing the goal and the data also would result in the development of a model/analytical technique.

In Chapter 4, how goal setting has to be embedded into the algorithm of a model is discussed. In a computational program, the objective function (e.g. GDP) and the constraint (e.g. emissions) are formulated so that the ‘optimal’ solution is found in the trade-off (e.g. between increasing GDP and reducing emissions). However, this chapter proposes to set the goal in the context of ‘direction’ rather than ‘speed’. When direction of green growth is set as the goal, the objective function might be ‘minimizing’ emissions/GDP, for instance, or keeping the level ‘appropriate’. The algorithm of the model needs to be reconsidered.

In Chapter 3, how data could frame the scope of analysis is identified. Spatial and temporal boundaries and the degrees of vertical and horizontal integration, as summarized in the ‘list of general questions regarding integration in risk assessment’, are to be critically considered so that data availability does not distort the analysis and the result.

The mission of industrial ecology is ‘finding innovative solutions to complicated environmental problems’ (ISIE, 2009). With the three models and the three analytical techniques, the basic equations are reviewed (see eq. 1-10 in Chapter 1) and applied to each topic (sustainable consumption and production, risk assessment and a low-carbon society), which shows each specific interaction between the model/analytical technique, the data and the goal.

One final remark: Three elements—data, model and goal—are mentioned above. Though this might not be a proper scientific approach, it could be said that data represents your body and the physical world, a model is how your logical and physical systems operate and a goal is what your heart and the world wants. Concerning body and logic, Hakuin Ekaku from Zen asked:

*Two hands clap and there is a sound; what is the sound of one hand?*

The answer cannot be reached only through rationality. Meanwhile, regarding heart and logic, Ludwig Wittgenstein from philosophy reached the point where rationality remains quiet:

*Whereof one cannot speak, thereof one must be silent.*

I believe that we just need the ‘two’ together to talk.

### **3. List of Answers to Meta- and Specific Research Questions**

*Research Question 1:* Do decomposition and attribution analyses explain cause and effect for the future?

*Answer 1:* Attribution analysis does not include the rebound effect. Decomposition and attribution analyses can be applied to static LCI, not to the dynamic Leontief model. In marginal analyses, the static and dynamic models would behave in different manners. Thus, it cannot be concluded that decomposition and attribution analyses explain cause and effect for the future.

*Research Question 1.1:* Is the ‘reverse’ indicated in Chertow (2000) identified between the equations of decomposition and marginal analyses in LCI?

*Answer 1.1:* The ‘reverse’ exists between the two analyses; the difference in their mathematical formations and operations are subtle but this enables decomposition analysis to determine the contribution of change in each variable to the total change of environmental intervention between two time periods in the past and marginal analysis to foresee environmental intervention in the future caused by a change in variables.

*Research Question 1.2:* Does technology with efficient use of energy and materials lead to less environmental impacts or, on the contrary, more?

*Answer 1.2:* In the static model (i.e. LCI) such technology leads to less environmental



impacts, while in the dynamic model (i.e. dynamic Leontief model) it would lead to more growth and thus more environmental impacts in the future.

*Research Question 1.3:* Does less consumption lead to less environmental impacts or, on the contrary, more?

*Answer 1.3:* In the static model (i.e. LCI) less consumption leads to less environmental impacts, while in the dynamic model (i.e. dynamic Leontief model) it would lead to more growth and thus more environmental impacts in the future.

*Research Question 1.4:* How can the different behaviours between the static and dynamic models be interpreted?

*Answer 1.4:* One interpretation is that static LCI has the driver for energy and material flows in a consumption system as external demand while the dynamic Leontief model has the driver in a production system through a mechanism of generating surplus. Thus, both types of logic have to complement each other

*Research Question 2:* Can attribution analyses investigate data uncertainty and supplement a lack of data for the cases whose causes took place in the past?

*Answer 2:* With the support of a general technology database which contains coefficients of technology, emissions and impact, attribution analysis can clarify which data is uncertain and deficient and to what degree this uncertain/deficient data affects the results and shall be improved.

*Research Question 2.1:* Which scopes (e.g. time, place, chemicals, stage) shall be taken into account?

*Answer 2.1:* As in the following list of general questions regarding integration in risk assessment (see Table 1 in Chapter 3), spatial and temporal boundaries and vertical and horizontal integrations shall be specified to clarify which data and analysis is uncertain/missing.

**Table 1 (numbering for Chapter 3). General list of scopes for Research Question 2.1.**

|  |
|--|
| Spatial Boundary   |
| S1. Are proper geographical issues addressed? How is identified the area at risk?                  |
|  |
| Temporal Boundary  |
| T1. From which year, should the data of flows of pollutants be gathered?                           |
| T2. Are historical stocks as well as yearly flows of pollutants in different media considered?     |
|  |
| Vertical Integration   |
| V1. Is the mechanism between production, technology and emission clearly understood?               |
| V2. Is the relation between emission and concentration of pollutants in media clearly established? |
| V3. Does the exposure from concentration to targets at risk get clarified?                         |
| V4. Does the exposure fully explain the damage of targets (e.g. in terms of health effects)?       |
|  |
| Horizontal Integration   |
| H.1 Are the whole location of emissions (i.e. point source, non-point source) considered?          |
| H.2 Are the entire emission of pollutants covered?   |
| H3. Are all the pathways through different media (i.e. air, water and soil) examined?              |
| H4. Are the whole range of risks on each target (e.g. people, agricultural field) considered?      |
| H5. Are locations, pollutants, pathways and targets at risk considered simultaneously?             |
| H6. Are important synergetic or antagonistic reactions taken into account?                         |

*Research Question 2.2:* Are registered emissions and calculated emissions from production data consistent (uncertainty of data)? Can the calculated ones supplement a lack of data?

*Answer 2.2:* Considerable uncertainty of data was observed and important missing data was specified in the case study. If data on production levels and processes and information about abatement technology changes in a focused site are publicly registered, it would be possible for ‘third parties’ to run analyses with general databases of technology to check for consistency. This provides incentives for constructing better public databases that could supply reliable data from industrial operators and reduce the burden of regulatory authorities to deal with uncertain/deficient data.

*Research Question 2.3:* Are monitored emission concentrations in the air and calculated concentrations from emission data consistent (uncertainty of data)?  
Can the calculated values supplement a lack of data?

*Answer 2.3:* Considerable uncertainty of data was observed and important missing data was specified in the case study. Considering the fact that only seven pollutants had been monitored at the Gela site while LCA databases often deal with hundreds of pollutants and the EPER lists 50 pollutants, calculated emission concentrations greatly supplement a lack of data.

*Research Question 3* How are objectives and constraints are established and what shall be the paths (e.g. speed or direction)?

*Answer 3* Consistency between basic indicators of models and those of objectives and constraints would help to derive solutions. However, the latter is not necessarily the same as the former. For instance, even though GDP would be maximized in an economic model (supposedly this is the nature of an economic system), it might be desirable for society to set GDP per capita as its objective. In addition to this, in economic models, optimal paths are often found exactly on the constraints. However, considering that it would take time and money to divert a certain direction of growth to the other, it is worth considering the degree to which the path is diverted from the constraints; the direction of green growth would be more important than speed of economic growth.

*Research Question 3.1:* Starting from the IPAT equation, what are the basic indicators, objectives and constraints that shape the arguments of LCSs?

- Whether the object of LCS is GDP or GDP/capita?
- Whether the main object of LCS can be measured by economic indicators such as GDP and GDP/capita?

*Answer 3.1:* As for the indicators, in addition to IPAT variables, another indicator, land per capita, is important for LCSs because the social visions of LCSs are related to how land is used. As an object, in addition to total GDP and GDP per capita, social indicators such as the Human Development Index (HDI) and a satisfaction with life index are worth considering since setting objects for LCSs would be a

much more complicated task than setting economic indicators. For constraints, the rationale for constraints on emissions (tons) and emissions per capita (ton/capita) shall be given consistent logic between them, regarding the carrying capacity of climate and equity issues.

*Research Question 3.2:* What are the historical paths of several countries and what can be said for their future paths toward LCSs?

- Does the path give priority to the speed of maximizing the objects or to the directions which liberate the path from the constraints?

*Answer 3.2:* Not only GDP and technology but also socioeconomic indicators such as affluence and population shall be properly integrated in consistent visions and strategies toward LCSs.

- If 'weak sustainability' holds true where ecological and economic/social capital can be interchanged, the priority might be given to speed. However, if 'strong sustainability' is needed, minimum amounts of a number of different types of capital (economic, ecological and social) should be independently maintained in real physical/biological terms (Ayres, 1998). Thus, running on the edges of ecological constraints might not be a desirable situation.

## 4. References

Ayer, R. U., J. C. J. M. van den Bergh and J. M. Gowdy. 1998. Viewpoint: Weak Versus Strong Sustainability, Tinbergen Institute Discussion Papers, number 98-103/3.

Boulding, E. Kenneth. 1989. *Three Faces of Power*, Sage Publications.

Chappin, E. and Dijkema, G. (2008) Towards the assessment of policy impacts on system transitions in energy, 31st IAEE International Conference, Bridging Energy Supply and Demand: Logistics, Competition and Environment, Istanbul, Turkey, IAEE.

EC, 2000, Communication from the commission on the precautionary principle, commission of the European communities, Brussels, 2.2.2000, COM(2000) 1 final

Huppes, G., M. Ishikawa. 2009. Eco-efficiency guiding micro-level actions towards sustainability: Ten basic steps for analysis. *Ecological Economics*, 68 (6), 1687-1700.

ISIE, 2009. Web page of International Society for Industrial Ecology.  
<http://www.is4ie.org/history>