博士論文

Comprehensive Material Flow Analysis for Sustainable Resource Management of Developing Economies

(発展途上国経済における持続可能な資源利用のための包括的マテリアルフロー分析)

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Contents

Abstract

Comprehensive Material Flow Analysis for Sustainable Resource Management of Developing Economies

（発展途上国経済における持続可能な資源利用のための包括的マテリアルフロー分析）

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The global warming and climate change are real and have become a threat to all life on the earth. The natural resource is currently extracted and served greedy human-consumers with unprecedented rate and if the trend keeps rising or even remains constant with a current rate, there would not be the remaining virgin resource for coming generations. Scientists, policymakers, inventors, entrepreneurs, thinkers, global citizens, all are finding solutions and making progress to combat climate change and looking toward sustainable development. With the current population growth, expanding of urbanization, and industrialization, these challenges are tickling the global movement seeking sustainable development pathways.

To establish the ideal sustainable development pathways, the understanding of sustainable resource management is crucial. Industrial Ecology (IE) is the multi-disciplinary field that has provided analytical frameworks and indicators to support sustainability for several decades. Material Flow Analysis (MFA) is the important branch in IE that providing the knowledge of the socioeconomic systems in physical dimensions. It has been used as the high-level policy indicators in European countries, Japan, China, and now also integrated into the benchmark indicators of Sustainable Development Goals (SDGs). In this dissertation, Economy-Wide Material Flow Analysis (EW-MFA) is conducted for the case studies of developing economies. The Eurostat's EW-MFA guidelines are used as the main analytical framework; however, it is designed with the experiences in developed countries. The applicability of the guideline to developing countries was checked, and the needed improvements for the estimation approaches were proposed specifically for developing countries.

In Chapter 1, the general background of the dissertation was discussed. The contents from this chapter include the current global environmental challenges, the principle theory of industrial ecology as the analytical framework providing the information to support sustainability. The motivations of the current research were provided which lead to the objectives of this study.

Chapter 2 presents the systematic literature review of the evolution of MFA in ASEAN's Industrial Ecology Community by using the integrated approach of Social Network Analysis and Text-mining. The methodology applied in this chapter was useful to provide a better understanding of scientific mapping. In parallel, the results pinpointed the popular research area in IE, as well as providing the discussion for the potential further research topics in ASEAN countries. The lack of MFA studies in the region was confirmed.

Chapter 3 presents the main methodology of this dissertation. It starts with the introduction of the core framework, Eurostat's EW-MFA compilation guideline. Based on the guideline, the classification of indicators and material categories were organized. The potential data sources, based on the suggestions of the guideline and author's experiences, for compiling EW-MFA were listed. Based on the limitations of the direct implementation of Eurostat's guideline to the case study of developing countries, I suggested several improvements for estimation approaches of the data that missing in the official statistics. The approaches for handling the uncertainty of EW-MFA results were also demonstrated.

Chapter 4 is the implementation of the methodological improvements in the previous chapter. The comprehensive EW-MFA (full mass balancing EW-MFA) was conducted for the case study of Lao PDR. The results granted insight into understanding of physical dimensions of Lao PDR's socioeconomic system. This was the first time that the comprehensive EW-MFA was conducted based on the local knowledge and national statistical data, with minor support from international databases to fill the data gaps. I also showed how the results from this study improved by comparing to the empirical data from UNEP International Resource Panel's database (http://www.resourcepanel.org/global-material-flows-database). The discussion on whether to use material flow indicators based on the direct material flow basis or based on raw material equivalent basis was briefly discussed.

In Chapter 5, another case study of developing country, Bangladesh, was included to show how the improved framework and the estimation approaches proposed in this dissertation could be implemented to provide more realistic data for other developing countries. The analysis in this chapter focused only on the main indicators of EW-MFA, including Domestic Extraction account (DE), Trades account (Imports and Exports), and derived indicators from EW-MFA framework such as Domestic Material Consumption (DMC), and Physical Trades Balance (PTB). Resource efficiency indicators, namely Resource Productivity and Resource Intensity were also included. To validate how the accounting is improved, the result was once again compared to the UNEP International Resource Panel's database.

Resource efficiency, which is the fundamental concept of sustainable resource management, was discussed in Chapter 6. Extended the results of the comprehensive EW-MFA of Lao PDR, resource efficiency analysis was conducted. The general concepts of resource efficiency and some examples of implementation in sustainable resource management policy designs were discussed at the beginning of the chapter. Resource efficiency indicators of Lao PDR, namely resource productivity, resource intensity, and emission intensity, were calculated. As Lao PDR is currently in the beginning of infrastructure development period, the analysis shows that the resource efficiency of Lao PDR is decreasing. The IPAT (Impact = Population * Affluence * Technology) equation was used to explore the driving forces of resource consumption in Lao PDR in different time period which chosen based on the time interval of the Five-Year National Socio-Economic Development Plan. The analysis showed that throughout all periods, population and affluence contributed to increasing domestic material consumption with affluence (growth in per-capita GDP) being the most important factor. Based on the resource efficiency indicators, the policy implication for Lao PDR was discussed.

Chapter 7 shows how the EW-MFA data could be extended by integrating the MISO model (Material Input, Stocks and Output), developed by Krausmann et al. (2017), to provide the premature insight of the material stocks which provide services for society such as shelter, mobility, communication, and could be considered as human well-being measurement matric. The results showed that almost all the stocks-building materials (except timber) have been exponentially increasing since the beginning period of study. At the beginning of the studied period, the growth pattern of total stocks per capita of Lao PDR was following other developing countries, but within the last decade, it already outpaced the level of some other developing countries in the rest of the world. Comparing to the average level of global stocks per capita in 2010, with the current rate of accumulation, the level of stocks per capita of Lao PDR is likely to surpass the global level soon. However, when compared to other industrial countries, the level of stocks per capita of Lao PDR is still relatively low. This is a very good opportunity for the country to leapfrogging the resource use to optimal saturation level by increasing resource efficiency through system-wide policy design, technology advancement, and innovations.

Chapter 8 is the conclusions and recommendations of the dissertation. The dissertation was summarized including the main messages from the dissertation's findings. The contribution to the scholarly communities in terms methodological improvement was summarized here. The suggestions for the policy implications of the research findings were provided. The recommendations for practitioner and researchers in terms of the future works to improve the EW-MFA in developing countries were given. Finally, by providing the recommendations for sustainable resource management for Lao PDR, the usefulness of the improved EW-MFA was confirmed, and the main objectives of this dissertation were achieved.

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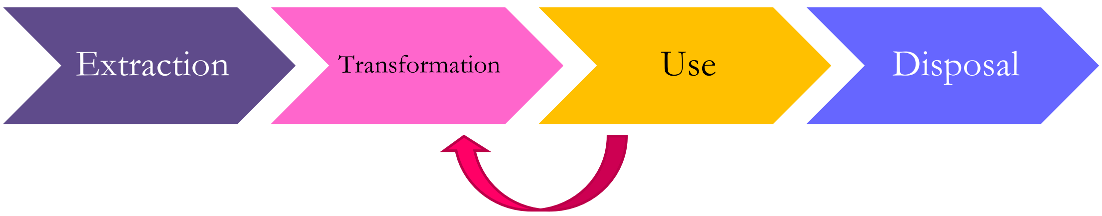
CHAPTER 1
INTRODUCTION

1.1 Why do we need sustainable resource management?

Natural resource, which could be categorized as biotic and abiotic, renewable and nonrenewable, or terrestrial and marine, are fundamental inputs to fuel our socioeconomic systems. Currently, human has extracted the natural resource at an unprecedented rate and expected to further increase in the coming decades (UNEP 2016). Resources extracted from planet earth's boundary provide food, materials for construction of the building and other infrastructure, raw materials for the production of commodities, materials for energy, in a form of biomass, metal, non-metallic mineral, and fossil fuels.

The whole life-cycle of resource comprises of extraction phase of primary resource from earth's biosphere, transformation phase of resource into goods, services, and infrastructure, use phase include consumption of food, consumer goods, services, and mobility, and the last phase is final treatment and disposal (Figure 1-1). Across the whole life-cycle of resource use, environmental impacts, including emissions, climate change, environmental degradation, deforestation, for instance, can exist in all phases. Thus, in order to ensure sustainable resource use, increase resource efficiency all across the whole life-cycle of the resource use is essential (IRP 2017).



Source: amended from IRP (2017)

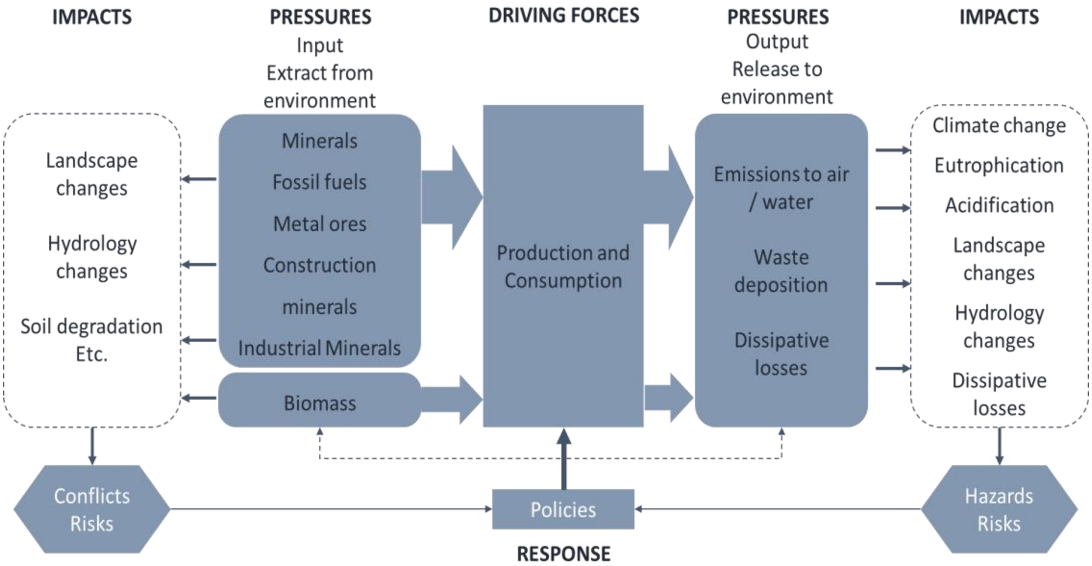
Figure 1-1 Life cycle of resource use

1.2 Defining sustainable resource management

IRP defined sustainable resource management as: "Sustainable resource management means both (a) ensuring that consumption does not exceed levels of sustainable supply and (b) ensuring that the earth's systems are able to perform their natural functions (i.e. preventing disruptions like in the case of GHGs affecting the ability of the atmosphere to regulate the earth's temperature)" (UNEP IRP 2018a).

"It requires monitoring and management at various scales. The aim of sustainable resource management is to ensure the long-term material basis of societies in a way that neither resource extraction and use nor the deposition of waste and emissions will surpass the thresholds of a safe operating space" (UNEP IRP 2018a).

1.3 How to measure the sustainable resource management?



Source: amended from Bringezu et al. (2016)

Figure 1-2 Drive Force-Pressure-State-Impact-Response (DPSIR) framework for socio-industrial metabolism

International Resource Panel (IRP or UNEP IRP are used interchangeably) of United Nations Environment Programme (UNEP) acknowledges that the current global production and consumption pattern is unsustainable and the transition to the sustainable one is needed to ensure the sustainable development (IRP 2017). In order to pursue sustainable resource management, good governance and management based on sound scientific information, data and indicators are necessary (Bringezu et al. 2016). Based on Drive Force-Pressure-State-Impact-Response (DPSIR) framework (see Figure 1-2), in order to quantify the "pressures" in the input and output sides, Material Flow Analysis (MFA) framework is commonly used.

MFA is an analytical framework applied to study the material throughputs in extraction, chemical transformation, manufacturing, consumption, recycling, and disposal processes (Bringezu and Moriguchi 2002). MFA has been emerging and expanding its applications to various sectors. It provides valuable information to stakeholders in the policy segments, including individual firms, government agency as well as international organizations (Fischer-Kowalski et al. 2011). Economy-wide material flow accounting/analysis (EW-MFA) is one of six MFA categories based on the classification of Bringezu and Moriguchi (2002). Employing EW-MFA, it allows us to assess physical dimensions of the national economy and reveal environmental burdens associated with resource use.

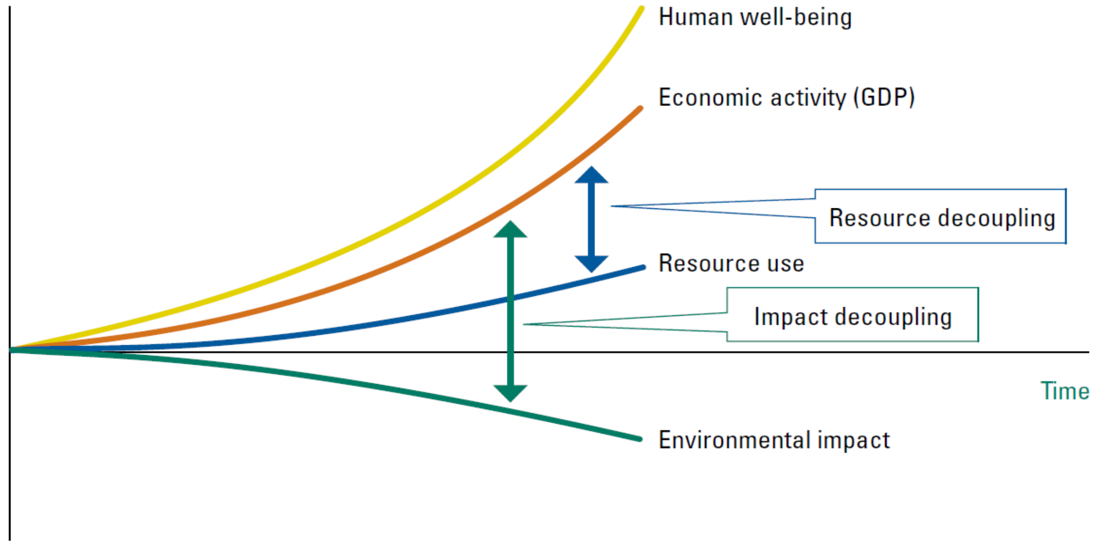
Based on the EW-MFA results, the resource efficiency, which measures how efficient we use the resource in the socioeconomic system, could be calculated. Resource efficiency is the very important fundamental concept of sustainable resource management.

The main concept of sustainable resource management is increasing resource efficiency. Resource efficiency is very important for decoupling natural resource use from economic development while maintaining human well-being. Based on IRP's glossary, resource efficiency is defined as: "Resource efficiency is an overarching term describing the relationship between a valuable outcome and the input of natural resource required to achieve that outcome. It is the general concept of using less resource inputs to achieve the same or improved output (resource input/output). It indicates the effectiveness with which resource are used by individuals, companies, sectors or economies" (UNEP IRP 2018a). It should be noted that the concept of economic efficiency is significantly different from the resource efficiency mentioned throughout this dissertation. Regarding the definition, there are three main indicators for measuring resource efficiency as follows:

- Resource Productivity: it is measured by the economic outputs to be achieved by the amount of resource inputs. This could be broken down into material productivity, energy productivity, and labor productivity. Generally, the Gross Domestic Products (GDP) per Domestic Material Consumption (DMC) is commonly used to measure the resource productivity of the country.

- Resource Intensity: this indicator is the inverse of resource productivity and commonly measured in DMC per GDP.
- Emissions Intensity: this could be measured by the ratio of undesirable output, Domestic Processed Output (DPO) (solid, liquid or gaseous) per GDP.

Resource efficiency can be achieved by increasing resource productivity (value added/resource use) or reducing resource intensity (resource use/value added), which considered as the core concepts of "Decoupling". Decoupling is the fundamental concept in order to achieve higher resource efficiency. The IRP defines resource decoupling as: "… decoupling means removing the link between two variables…" (UNEP 2011). The decoupling could be referring to resource decoupling, which indicates the delinking of economic growth and resource use, or impact decoupling, which indicate the delinking of economic growth and negative environmental impacts. By innovations and systems-wide policy design, the double decoupling, which refers to delinking economic growth from resource use and from environmental impacts, could be achieved. Other than these concepts, the decoupling could be also evaluated by "relative decoupling" (the rate of resource use increase is lower than the rate of economic growth) or "absolute decoupling" (resource use declines while the economy grows). The illustration of the decoupling concept from the Decoupling report published in 2011 is shown below.



Source: UNEP (2011)

Figure 1-3 The illustration of decoupling concepts

1.4 Motivations of the study

The main motivation for this dissertation is to improve the framework for establishing the EW-MFA in developing countries to support the sustainable resource management. Several specific motivations are summarized as follows:

- The EW-MFA framework has been matured and has become the main analytical framework for sustainable development policies in the developed world. However, in developing countries, the EW-MFA is in the very beginning stage of development and application. This would require research and development based on local knowledge in order to adapt the framework that mainly developed in the European countries to be suitable with the characteristics of developing countries.

- The acceleration of global resource use is currently driven by rapid resource extraction/use in many developing countries in the Asia-Pacific region. However, the current knowledge of resource use in these developing countries relies on international databases. Conducting the EW-MFA based on local knowledge and national statistical data is recommend by the Eurostat to reflect the realistic situation of resource use in such county.

- In many developing countries, environmental policy is in infancy stages. This is due to the lack of the human resource needed. Through capacity building, technical enhancing through supporting by scientific results would help to boost the development of environmental policies in such developing countries.
- Lao PDR is chosen as the case study for full balance EW-MFA for several reasons. First of all, Lao PDR is currently lack of capacity, especially in the environmental oriented statistics. Second, Lao PDR is considered to start increasing its resource use due to the rapid socioeconomic development. The flows and stocks of materials would be important to ensure the sustainable development of the country.
- Bangladesh is chosen as another case study to perform the EW-MFA based on improved framework proposed in this study to show how the improved EW-MFA could be implemented in other developing countries, which has quite difference characteristics, compared to the previous case study.

1.5 Objectives

The objectives of this dissertation are:

(1) to review related literature from developing world to discover the current situation of industrial ecology

(2) to assess the applicability of the MFA framework based on Eurostat guideline for developing countries

(3) to improve the estimation approaches for missing data in the official statistics and construct the comprehensive EW-MFA to derived the resource efficiency indicators for the case studies of Lao PDR and investigate the applicable of the improved approaches with another case study of Bangladesh

(4) to conduct dynamic MFA for developing country to assess the evolution patterns of material stocks accumulated in the socioeconomic system

(5) to provide recommendations for policymakers about trends in resource use, resource efficiency, and waste and emissions to promote the use of MFA indicators in sustainable resource management policy design.

CHAPTER 2
Evolution of MFA in ASEAN's Industrial Ecology Community

2.1 Background

Industrial ecology (IE) is the multidisciplinary research framework intended to study the flows of energy and materials related to human activities in the biosphere (Erkman 1997). Earlier in 1994, the president of the US National Academic of Engineering gave the concept of IE as "Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effects of those flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resource" (White 1994). There is a more extensive definition of IE given by Graedel and Allenby (1995) which contribute to extend the IE to other disciplines and provide various indicators and proxies to support sustainability (Graedel and Lifset 2016). According to Graedel and Lifset (2016), IE comprises Life-Cycle-Assessment (LCA), Design for Environment, Material Flow Analysis (MFA which sometime Material Flow Accounts is used interchangeably), Socioeconomic Metabolism, Input-Output Analysis, Urban Metabolism (UBM), and Industrial Metabolism.

Experiences from developed countries clearly illustrate that IE could provide tools and indicators for sustainable resource management policy design (European Commission 2017; Takiguchi and Takemoto 2008). A literature also show how IE knowledge, specifically saying MFA indicators, contributes to the policy implementations in emerging economy like China, which MFA indicators were used to evaluate the progress of circular economic development in China (Mathews and Tan 2016). In another least-developed country liked Lao PDR (or Laos), Vilaysouk et al. (2017) also illustrated how EW-MFA results could be utilized for reporting the progress of SDGs targets.

These works are some examples of the implementation of MFA framework in the policy communities to support sustainable resource use. To explore further possibility of the IE knowledge implementations in other disciplines, the bibliometric analysis and Social Network Analysis (SNA) are often used to evaluate the trends of researches in the

IE field (Merli et al. 2018; Li et al. 2018b; Li et al. 2018a; Zanghelini et al. 2016; Wang et al. 2016; Sara and P. 2015; Newell and Cousins 2015; Hou et al. 2015; Chen et al. 2014; Chang et al. 2014; Weslynne 2008). The first scientific mapping involving bibliometric and network analysis is the work of de Solla Price (1965) back in 1965.

However, most of these studies focus on the narrower specific research area instead of investigating the IE discipline as a whole for instance the bibliometric were applied to investigate the LCA studies of bioenergy (Li et al. 2018a), solid waste reuse and recycling (Li et al. 2018b), waste-to-energy (Wang et al. 2016), resilience and complexity in industrial ecology (Sara and P. 2015), urban metabolism (Newell and Cousins 2015), LCA (Hou et al. 2015; Chen et al. 2014), industrial symbiosis (Chang et al. 2014), industrial ecosystem (Weslynne 2008), as well as circular economy (Merli et al. 2018).

From the generic bibliometric approach employed in works mentioned above, the results provide general descriptive information of the publications, such as the trends of publications number, the influenced journals in the field, popular keywords, words co-occurrence, authors' productivity, institute collaborations network, as well as author collaborations network. But by using certain algorithms in the network analysis framework, it could also provide interesting characteristics of the studied network. For instance, modularity class algorithm could identify the clusters (communities) of the nodes in the whole network, which then the communities could provide information referring to the shared characteristics of such nodes in the communities.

In this study, I aim to investigate the evolution of IE knowledge-based in ten member countries of ASEAN: Association of Southeast Asia Nations (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam) by using the bibliometric and extend the results involving the innovative Natural Language Processing (NLP, the text-mining approach) for interpreting the main research theme of publications clusters. This is the first time, that bibliometric analysis and text-mining are employed together to exploit the evolution of IE knowledge-based in ASEAN countries. In terms of methodology, the current study differs from other as it could provide a better understanding of the general bibliometric analysis by integrating text-mining to explore deep down into the unstructured text data of the title and abstract of publications in the dataset. I employed text-mining to determine the main research theme of the identified communities, which classified by modularity class in the citation network. Overall, this chapter would provide spacious perspective of the evolution of IE discipline in ASEAN in more detail rather than the general bibliometric results. The methodology proposed in this study could show how the general bibliometric could be integrated with the innovative text-mining technique to provide the better understanding for scientific mapping. In parallel, the results pinpoint the popular research area in IE, as well as providing the discussion for the potential further research topics in ASEAN countries.

2.2 Methodology

2.2.1 Research framework

Figure 2-1 shows the workflow of the methodology of this study. There are three analytical techniques were employed in this study i.e. bibliometric analysis, social network analysis (SNA), and text-mining.

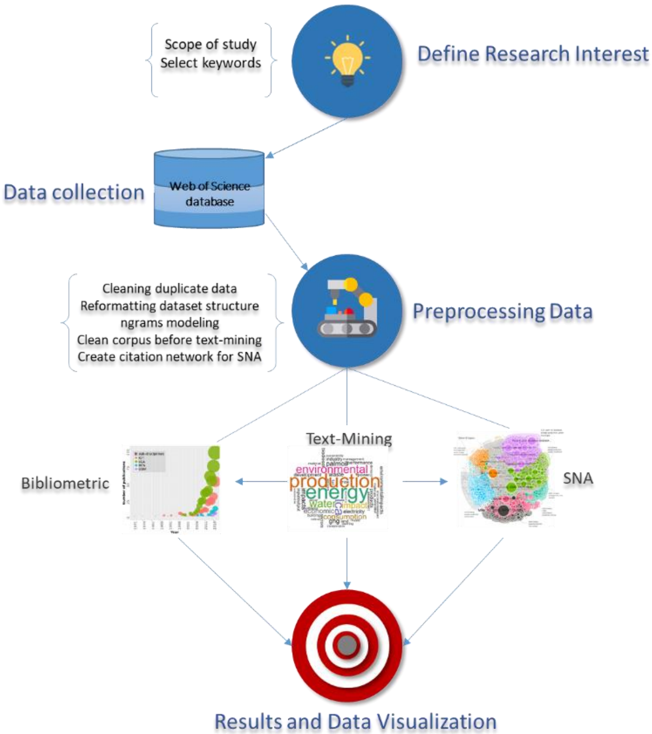


Figure 2-1 Research Framework for the Extensive bibliometric analysis by integrating text-mining techniques

Bibliometric is a quantitative statistical method that widely used to study the evolution of publications in the scientific communities (Ellegaard and Wallin 2015). Social Network Analysis is a sub-discipline of social science aiming the study of the relationship between social entities (Wasserman 1994). It is based on network and graph theories and widely employed to study citation and co-citation network, collaboration network, and other forms of social interaction network (Otte and Rousseau 2002). In this study, bibliometric was applied to study characteristics of publications related to IE in ten ASEAN countries, followed by the network analysis investigating the citation network aiming to obtain clusters of publications by the modularity algorithm (Blondel et al. 2008). Generally, in bibliometric research, the network analysis which applied to co-words network or collaboration network, the main topic of the nodes clusters could be easily interpreted. But for the network of the publication citations, in general, the cluster labeling was done manually (Fahimnia et al. 2015), which sometime might lead to inaccurate interpreting results and time consuming when the dataset is getting bigger. Thus, in this study, the text-mining technique was used to fulfill this research gap for identifying the context of the research theme of in each cluster of publications. The detail procedures are presented as follows.

2.2.2 Data preparation

The dataset for this study is obtained from multiple quarries from the Web of Science Core Collection (WOS) database in full record and cited references format. The year of publication cover from 1971 to 2017. To search the information of publications in IE field from the database, these notable sub-disciplines of IE which includes Life-Cycle-Assessment (LCA), Material Flow Analysis (MFA), Input-Output analysis (IOT), Urban metabolism (UBM) were used. Socioeconomic metabolism, Industrial metabolism, and Industrial symbiosis keywords were not included due to low number of publications from the database query which specify to the research in ASEAN countries (less than 0.5% of total publications in the dataset). To scope the query results for research related to ASEAN countries, ten countries name in ASEAN were used as the filter in the "topic" field of WOS's database. The publication types included in the dataset are journal article, proceeding, review, book chapter, meeting abstract, and communication letter. I limited the scope of study by include only publications in English. The duplications of publications data from different queries were removed in the data preparation process.

2.2.3 Bibliometric analysis

R language is the main analytical environment for this study. As this study intended to trace the evolution of IE researches differentiated by individual country, labels of the countries name and the IE sub-disciplines keywords were attached to the original dataset obtained from WOS by my developed R script. I then analyzed trends of the publications classified by the IE sub-discipline and by country. The publications' keywords and abstracts were assessed. Distribution of the publications to each journal was also analyzed.

Network analysis is employed and contribute to understanding of the citation network in the dataset. I constructed the citation network from cited reference information that obtained from the WOS. Input data for the network analysis was coded in R. I then used an open source software, Gephi version 0.9.2, for the network analysis. Gephi is network analysis software with a simple user interface. There are many built-in statistical features and algorithms for network analysis such as Betweenness Centrality, Closeness Centrality, Network Diameter, Clustering Coefficient, PageRank, Community detection (Modularity Class). In this study, I used in-degree as the main measurement parameter to detect the important publications that highly cited by other publications in the studied network. In visualization, the bigger size of the node, the more citations they have. Another score obtained by network analysis, namely authority score, was also used to find the influential publications of IE in the region. I used the modularity algorithm to cluster the nodes into smaller communities (clusters of publications). The nodes in the same community more likely shares similar characteristics through the relationship of their citation patterns. In previous studies, to determine the topic of the communities detected, they rather referred to the words itself (in case of co-words analysis network), or it could be done by hand labelling inferring the information of the node in such cluster (Fahimnia et al. (2015), p.109). In this study, to understand the research theme of such clusters, I applied text-mining techniques to the publications title and abstract. The VOSViewer version 1.6.8 was used to analyze and visualize the co-words network and collaboration network of IE researches in ASEAN. The details of text-mining are explained in the following section.

2.2.4 Text mining

Text-mining or text-analysis is a method to transform unstructured-text data into a meaningful quantitative form for further analysis. Text-mining tools include sentiment analysis, topic modeling, document classification, and word frequency analysis (Grubert 2017). Recently, topic modeling is widely applied to study topics of a large text corpus of a collection of documents. In this study, the number of publications in the dataset is relatively small compared to the original paper of the topic modeling (Blei et al. 2003). Thus, I selected the word frequency analysis instead, to analyses the publications' title and abstract. This approach was applied to the corpus of all publications in the studied dataset, as well as a sub-corpus of the obtained node clusters to identify the research themes of such publications clusters.

In this study, the word frequency modeling was accompanied by n-grams language processing model (n-grams is a sequence of *n* word of a given sample of text). Usually, even the most famous and successful Laten Dirichlet allocation (LDA) topic modeling approach (Blei et al. 2003), the topic modeling is performed following the bag-of-words approach, which results sometimes did not correlate with common human-understanding-liked topic (Nokel and Loukachevitch 2016) and needed human interaction to improve inferred topics obtained from the model (Hu et al. 2014; Boyd-Graber et al. 2007). Nokel and Loukachevitch (2016) demonstrated that by cooperating n-grams and multiword terms into topic modeling the results could be enhanced. Similarly, the corpus of the dataset in this study also contains a lot of important keywords that are not a unigram (n equal to 1). Thus, the bigram and trigrams (n equal to 2 and 3, respectively) modeling were employed to enhance the word frequency model's results. Text-mining analysis was performed in R environment with aids of various packages mainly tm package, tidytext, and tidyverse (Feinerer et al. 2018; tidyvers 2018; Silge and Robinson 2016).

2.3 Results and Discussions

2.3.1 Trends of IE Publications in ASEAN

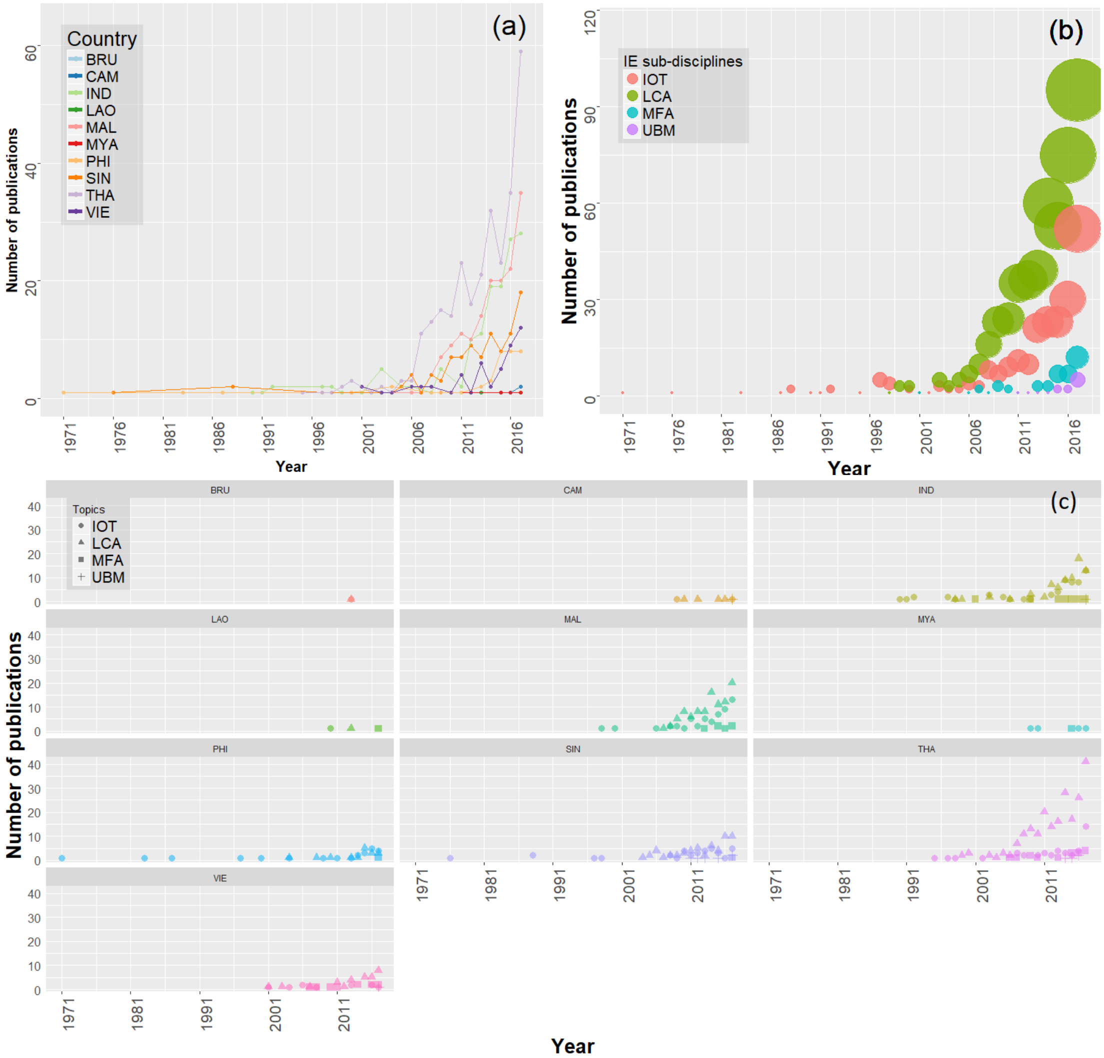


Figure 2-2 Trends of publications in Industrial Ecology discipline in ASEAN countries a) by countries, b) by IE sub-disciplines, c) details trends for individual country (note: Fig 2.a and Fig 2.b y-axis is different); BRU – Brunei, CAM – Cambodia, IND – Indonesia, LAO – Laos, MAL – Malaysia, MYA – Myanmar, PHI – Philippines, SIN – Singapore, THA – Thailand, VIE – Vietnam.

Figure 2-2 shows the evolution trends of publication in IE in ASEAN countries. Total 782 publications related to IE in ASEAN published from 1971 to 2017, collected from WOS, are investigated in this study, including 570 articles, 160 proceedings, 32 reviews, 16 book chapter, two book review, one meeting abstract, and a communication letter.

In the early 1970s to 1990s, there are some pioneer works in Philippines, Singapore and Indonesia, related to Input-Output analysis study (see Figure 2-2.a and Figure 2-2.b)

(Sicat 1971; Hsueh 1976; Cochrane 1990). The exponential increasing of IE research in ASEAN took place in mid 2000s, led by research related to case studies in Thailand, Malaysia, Indonesia, and Singapore. From 1971 to 1997, all of the publications related to IE implemented the Input-Output analysis approach (see Figure 2-2.b). The first LCA case study related to ASEAN is published in 1998 with the title of "A study of the ecological efficiency of new electrical technologies"(Rahman and Callwood 1998), followed by hundreds of publications published in the mid-2000s onward. Since then, LCA has led ASEAN IE knowledge-based, which evidently showing in the total number of publications. Publications of MFA originated in 2001 (Singh et al. 2001). The study implemented Socio-Economic metabolism to present MFA indicators in Trinket Island, the remote island between India and Indonesia. MFA publications have been slowly escalated since 2013, mostly contributed by the MFA application to case studies in Thailand, Vietnam, and Malaysia (see Figure 2-2.c). Urban metabolism (UBM) is the study of material and energy flows through the city based on material flow analysis principle (Dijst et al. 2018). While industrialization and urbanization happening across the globe, understanding of UBM is key for sustainable development (Newell and Cousins 2015; Dijst et al. 2018). In ASEAN, the first UBM study is "Dynamic modeling of Singapore's urban resource flows: Historical trends and sustainable scenario development" the conference proceeding published in 2011 (Abou-Abdo et al. 2011) (see Figure 2-2.b and Figure 2-2.c).

2.3.2 Publications performance and core journal of IE publications in ASEAN

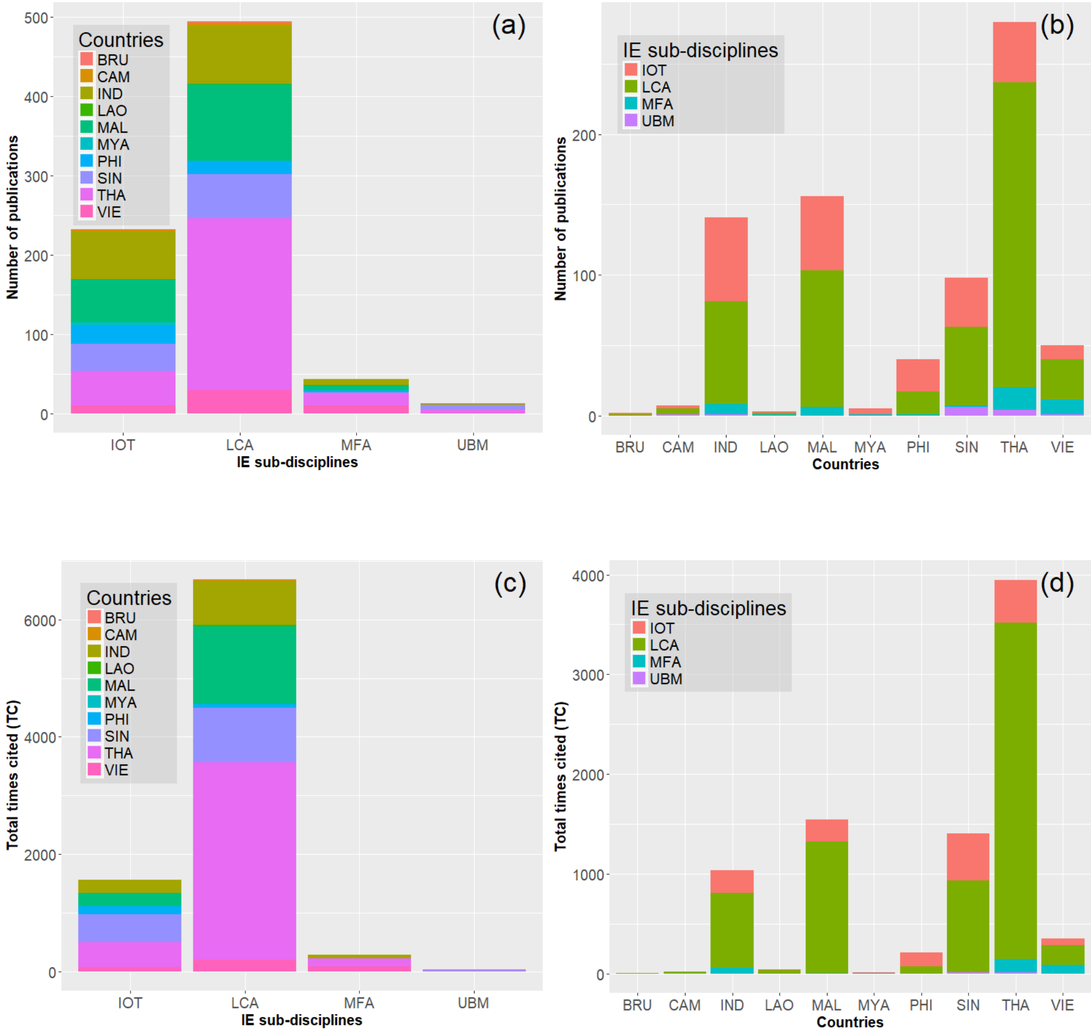


Figure 2-3 Performance of IE publications in ASEAN by a) total publication by IE discipline, b) total publication by countries, c) times cited by countries, b) times cited by IE disciplines

Figure 2-3 shows the performance of IE publications in ASEAN regarding total publications and total times cited (TC). Considering the total publications from 1971 to 2017, LCA dominates other IE disciplines in the dataset. In order to avoid the double counting when allocating the publication to the classified categories in this study, the publications that employed several IE frameworks for instance LCA and IOT, MFA and IOT, would be classified into the disciplines that mostly related to that certain framework which I mainly based on the query results given by WOS. Total publications related to LCA is 494 (63%), where IOT contribute to 232 publications (almost 30% of total publications, see Figure 2-3.a). MFA and UBM are two IE disciplines that has been contributed to less than 7% of total publications. Thailand is the most productive country with the total publications of 280, consisting of 217, 43, 16, 4 publications of LCA, IOT, MFA, and UBM, respectively. Case studies of Malaysia, Indonesia, and Singapore come after Thailand with the total publications of 156 and 141, 98 and sharing of research theme are almost identical. IE publications related to case studies in Vietnam and Philippines is under 50 publications. Research theme in Philippines mostly contributed by IOT (23 of 40 publications), while in Vietnam following similar trends in abovementioned countries. The IE publications regarding the case studies Cambodia, Myanmar, Laos and Brunei are far behind other countries, with the contribution of seven, five, three and two publications, respectively.

Measuring the performance of publications by times cited, the IE publications in ASEAN comes with the total of 8,555 times cited. Figure 2-3.c shows publications in LCA discipline is the most cited with total 6,682 times cited, 13.5 times cited per publications (hereafter TC/P) in average. IOT contributes to 1,566 times cited with average times cited of 6.8 TC/P. The MFA and UBM, which is quite young disciplines in ASEAN, acquire 279 and 28 times cited (6.5 and 2.1 TC/P). The total times cited of publications by countries followed the trends of total publications number. Calculated average times cited per publication by country, Singapore has the highest score as 14.3 TC/P, followed by Thailand, Laos, Malaysia, and Indonesia (14.1, 13.0, 9.8 and 7.3 TC/P).

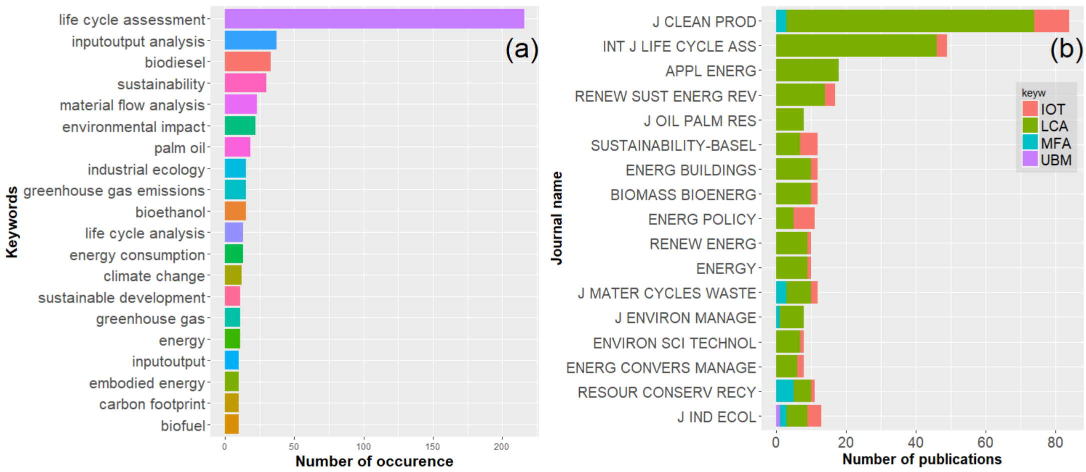


Figure 2-4 Top authors' keywords, b) Top Core Journal of IE publications in ASEAN

Word frequency analysis of keywords provided by the author(s) was performed to evaluate the theme of IE research in ASEAN. Figure 2-4.a shows the 20 most frequently used keywords. Results show that LCA is the most popular keyword with more than 200 times used, followed by keywords of other analytical frameworks such as input-output analysis, material flow analysis, life cycle analysis. The results also show that the keywords related to environmental concern such as sustainability, greenhouse gas emission, climate change, and sustainable development are frequently used by author(s). Biodiesel, bioethanol, biofuel and palm oil also pop-up in the top 20 keywords. Other keywords connected to the energy, for instance, embodied energy also found in the top keywords used.

Figure 2-4.b shows the core journal of IE publications in ASEAN. Journal of Cleaner Production (JCP) and International Journal of Life Cycle Assessment are the main targets for the researchers to publish their works. This is due to the main IE research theme in ASEAN is LCA. Other journals that related to energy, for instance, Applied Energy, Renewable and Sustainable Energy Reviews, Energy and Building, Biomass and Bioenergy, Energy Policy, Renewable Energy, Energy, and Energy Conversion and Management are also the places where IE researches were published. The main journal of IE discipline, Journal of Industrial Ecology (JIE), got only the total of 13 publications. Other journals that cover wider areas in sustainable and environmental such as Sustainability, Journal of Materials Cycle and Waste Management (JMCW), Journal of Environmental Management (JEM), Resources, Conservation & Recycling (RCR), Environmental Science and Technology, also host the IE publications in ASEAN. Regarding the distribution of IE research disciplines, only JIE covers all four IE disciplines defined in this study. Publications published in RCR, the interdisciplinary journal, cover three mains research theme of IE.

Figure 2-5 Word frequency analysis of the publication abstracts

In this study, the publications' abstracts were also performed in word frequency analysis. Figure 2-5 shows the most frequent words appear in the abstracts. Top 10 most frequent words found in the abstract highlighted in ten different colors and the bigger the word is the more important they are. From this figure, the theme of IE research could be simply identified as the context of the most frequent word used. Summarizing from the top authors' keywords and word frequency from abstract, one could be inferred that in ASEAN, IE analytical frameworks are popularly used to assess the environmental impacts, climate change, and sustainability for the energy production from biomass.

2.3.3 Citation network

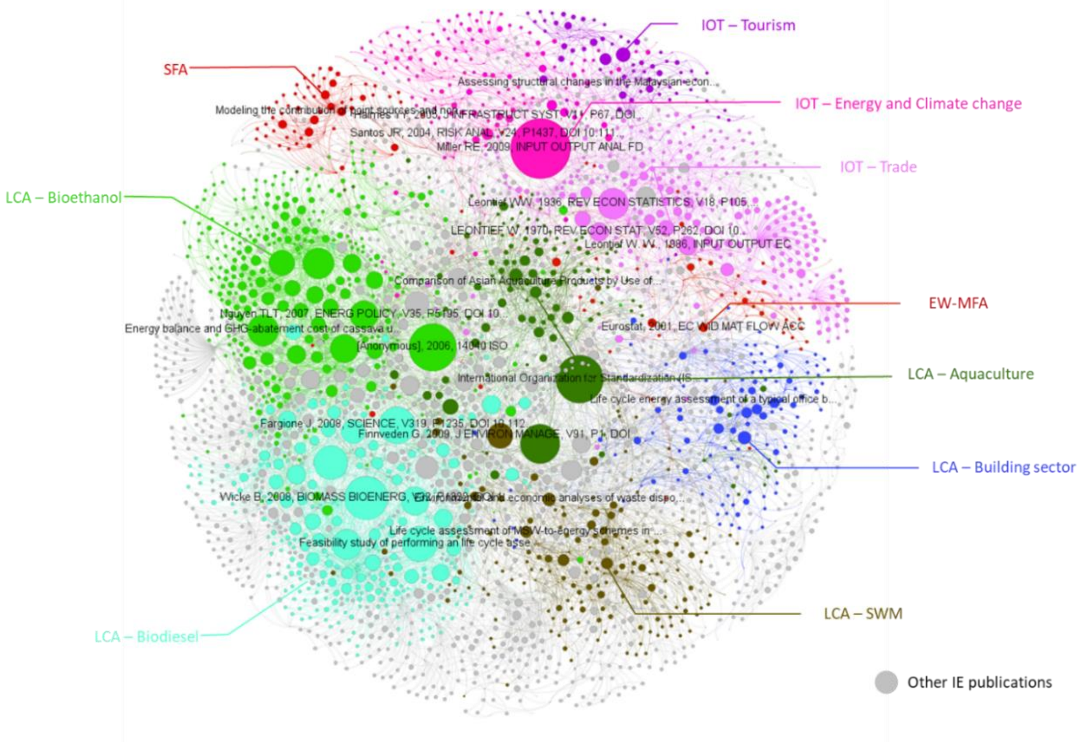


Figure 2-6 Network Analysis of IE Publications citation network in ASEAN (Please refer to online version for color figure)

Co-words network and citation network are commonly used to map the relationships between publications in the certain interested research fields (Wen et al. 2017). In this study, I used the citation network to derive the relationship of IE publications in ASEAN. Figure 2-6 shows the citation network of total IE publications in ASEAN, consisting only the citing nodes (publications) and cited nodes with at least two times cited. I used the in-degree to measure the importance of publications. The nodes share similar citation patterns are clustered into the same cluster by automated algorithm "Modularity Class". Then the publication titles and abstracts were used to extract the research theme of all publications in the cluster using word frequency analysis.

Ten main clusters of publication are detected (other smaller clusters are classified as the main theme, the Industrial Ecology cluster, the grey nodes). Using word frequency analysis technique, the main research theme of each cluster could be identified. The results from network analysis align with bibliometric results mentioned above as LCA also contributed to the major part of the network, consisting of four out of ten main clusters. The biggest publication cluster detected is the group of publications related to the LCA of biodiesel production from palm oil, secondly followed by LCA of bioethanol production from biomass (mainly from sugar cane, cassava). Third and Forth cluster also dedicate to the LCA domain, consisting of the LCA of solid waste management (SWM) and buildings sectors. The last cluster of LCA studies in ASEAN specifically devotes to quantification of the environmental consequences from the aquaculture sectors.

The research in IOT discipline related to ASEAN contributes to second most considering total publications and total times cited. From the citation network, three major clusters related to IOT discipline were identified. The biggest IOT cluster covers the researches applying IOT to study energy and climate change. Another cluster is the IOT analysis mainly focusing on trade and energy consumption. And the last IOT cluster is the study of economic impacts from tourism sectors in ASEAN's economy, which mainly leading by Singapore (in terms of the total number of publications and times cited).

For MFA, it could be divided into the EW-MFA and substance flow analysis (SFA) and they are the last two clusters in the top ten main clusters detected by modularity class in the studied network. The publications in EW-MFA cluster are mainly focusing on the resource efficiency, as the EW-MFA was originally designed to address such issues. In the SFA cluster, most of the publication discussing nutrient substances flow analysis including nitrogen and phosphorous that would leak to nature water body from urban infrastructures, agriculture and industry. The contribution of publications in SFA cluster mainly leading by the SFA study in Thailand and Vietnam.

2.3.4 Influential publications on IE research in ASEAN

The influential publications in the studied dataset are identified using two index scores from network analysis, "In-degrees" and "Authority" scores. The total times cited score obtained from WOS was also incorporated as a supplementary index to enhance the interpretation of the important publications.

Table 2-1 shows the top-ten publications using the in-degrees score. In-degree is the total direct links from other nodes (publications) in the network. The in-degree could be used to identify the important nodes in terms of the total times that they are cited from other nodes in the studied network. Regarding the in-degree score, the most important publication in the studied network is Miller and Blair (2009)'s work, the handbook of Input-Output analysis. The International Standard for LCA, ISO 14040 is also listed as the second and third influential nodes in IE research in ASEAN. Second and third nodes are actually identical, but due to the different citation format used by the publications' authors, it caused different in the reference records. I decided to keep these two nodes as different identities in the network to show how the inconsistence reference records used of the standards or organization reports affect the indexing results in the bibliometric analysis (see Figure 2-6 for more detail). If considering second and third as the single identity, ISO 14040 could be considered as the most influential node in the network. Other five publications are LCA of the palm oil and biodiesel. The studies include comparison of greenhouse gas emission (GHG) and environmental impacts from different crude palm oil production systems in Malaysia (Wicke et al. 2008), the discussion on how the conversion of rainforests, peatland, savannas, or grassland to produce biofuels from palms affect the increasing of GHG emission in the region (Fargione et al. 2008; Yusoff and Hansen 2007), as well as LCA of biofuel production in Thailand (Nguyen et al. 2007; Pleanjai and Gheewala 2009).

The authority score is another concept to spot the important publications in the citation network. Authority score is obtained by the Hyperlink-Induced Topic Search (HITS) algorithm, which used in the network analysis to identify the important nodes based on the mutual reinforcing relationship of hubs and authorities (Kleinberg 1999). Hub is the node that points to authorities. In another way, authority is the node that pointed to by hubs. A good hub is the node that points to many good authorities; a good authority is a node pointed to by many good hubs. At first, every node in the network is given the initial score of one. The hub and authority scores are iteratively calculated k-times until convergence. Ranking influential publications by authority score, the most influential publication in the network found to be Wicke and colleague' work of GHG emissions investigation from crude palm oil production in Boneo, Malaysia, followed by the feasibility study of performing a life cycle assessment on crude palm oil production in Malaysia (Yusoff and Hansen 2007), and another work of LCA of biodiesel production in Thailand (Nguyen et al. 2007). Ranking of these top-three publications almost identical to the ranking by in-degree score (when not including the IOS standard records references and Input-Output Analysis handbook). The ranking of influential publications by authority score gives not only the importance of the node in terms of the total in-degree that they have but it also includes the quality of the in-degree from the nodes that pointed to them. The influential publications in IE research in ASEAN are listed in Table 2-1 and Table 2-2. Looking at the total times cited index of these influential publications, for instance in Table 2-2, the publication ranked as the top by authority score has lower total times cited score than the publication ranked as the fifth. This indicates that the most influential publication for IE research in ASEAN do not necessarily be important for other networks, as well as the most important publication at the global level, does not necessarily be the most important publication in ASEAN. This could prove the concept that in order to identify the important publications in the certain specific area, using the index scores specifically calculated from the network analysis, for instance, "in-degree and authority scores", would provide favorable results.

Table 2-1 Top ten influential publications in IE research in ASEAN ranked by the in-degree score

No	Authors	Publication title	Year	Source	In-degree	Total times cited
1	Miller, RE; Blair, PD	Input-output analysis: foundations and extensions	2009	(BOOK)	43	
2	International Organization for Standardization (ISO)	ISO 14040	2006	(STANDARD)	34	
3	[Anonymous]	ISO 14040	2006	(STANDARD)	34	
4	Wicke, B; Dornburg, V; Junginger, M; Faaij, A	Different palm oil production systems for energy purposes and their greenhouse gas implications	2008	BIOMASS AND BIOENERGY	31	155
5	International Organization for Standardization (ISO)	ISO 14044	2006	(STANDARD)	28	
6	Fargione, J; Hill, J; Tilman, D; Polasky, S; Hawthorne, P	Land clearing and the biofuel carbon debt	2008	SCIENCE	26	1950
7	Yusoff, S; Hansen, SB	Feasibility study of performing an life cycle assessment on crude palm oil production in Malaysia	2007	INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT	25	92
8	Pleanjai, S; Gheewala, SH	Full chain energy analysis of biodiesel production from palm oil in Thailand	2009	APPLIED ENERGY	24	97
9	Leontief, WW	Quantitative input and output relations in the economic systems of the United States	1936	THE REVIEW OF ECONOMIC STATISTICS	22	717
10	Nguyen, TLT; Gheewala, SH; Garivait, S	Energy balance and GHG-abatement cost of cassava utilization for fuel ethanol in Thailand	2007	ENERGY POLICY	22	99

Table 2-2 Top ten influential publications in IE research in ASEAN ranked by authority score

No	Authors	Publication Title	Year	Source	Authority	Total times cited
1	Wicke, B; Dornburg, V; Junginger, M; Faaij, A	Different palm oil production systems for energy purposes and their greenhouse gas implications	2008	BIOMASS AND BIOENERGY	0.305189	155
2	Yusoff, S; Hansen, SB	Feasibility study of performing an life cycle assessment on crude palm oil production in Malaysia	2007	INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT	0.230091	92
3	Pleanjai, S; Gheewala, SH	Full chain energy analysis of biodiesel production from palm oil in Thailand	2009	APPLIED ENERGY	0.227603	97
4	Yee, KF; Tan, KT; Abdullah, AZ; Lee, KT	Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability	2009	APPLIED ENERGY	0.198324	118
5	Fargione, J; Hill, J; Tilman, D; Polasky, S; Hawthorne, P	Land clearing and the biofuel carbon deb	2008	SCIENCE	0.173072	1950
6	Reijnders, L; Huijbregts, MA	Palm oil and the emission of carbon-based greenhouse gases	2008	JOURNAL OF CLEANER PRODUCTION	0.171666	157
7	Achten, WMJ; Vandenbempt, P; Almeida, J; Mathijs, E; Muys, B	Life Cycle Assessment of a Palm Oil System with Simultaneous Production of Biodiesel and Cooking Oil in Cameroon	2010	ENVIRONMENTAL SCIENCE & TECHNOLOGY	0.141309	33
8	Choo, YM; Muhamad, H; Hashim, Z; Subramaniam, V; Puah, CW; Tan, YA	Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach	2011	INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT	0.135769	56
9	Stichnothe, H; Schuchardt, F	Life cycle assessment of two palm oil production systems	2011	BIOMASS & BIOENERGY	0.128813	35
10	Lam, MK; Lee, KT; Mohamed, AR	Life cycle assessment for the production of biodiesel: A case study in Malaysia for palm oil versus jatropha oil	2009	BIOFUELS BIOPRODUCTS & BIOREFINING-BIOFPR	0.125728	45

2.3.5 Co-words network

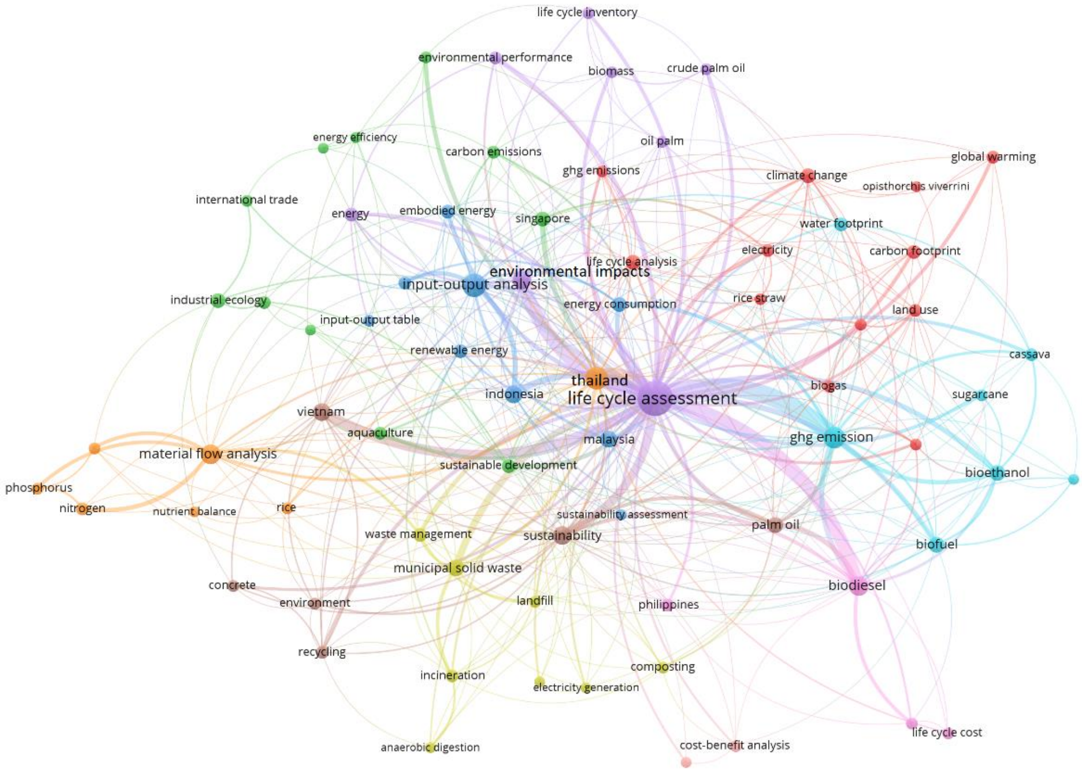


Figure 2-7 co-words occurrence network of IE publications keywords in ASEAN

From the co-words network of authors' keywords, major clusters could be found. The first cluster that has strong relation to LCA (life cycle assessment) node is a cluster of keywords related to bioenergy such as biodiesel, bioethanol, biofuel, bio gas (see Figure 2-7). Another cluster is keywords related to environmental concerns, for instance, greenhouse gas emissions, carbon footprint, global warming, climate change, land use, water footprint. One more group of keywords strongly connected to LCA node is solid waste management (SWM) keywords such as waste management, landfill, composting, incineration, for instance. Other groups are the group of keywords related to IOT and MFA framework.

From co-words network, LCA is found as the main node in the network that acts as the hub to connect different cluster. This implies that, from the co-words network, LCA is the hotspot for IE research in ASEAN. From this network, I found that LCA has the strong connection to keywords related to energy production from biomaterials. Co-words occurrence also shows that LCA is used to assess the environmental impacts and sustainability. LCA is also applied to assess the impacts from SWM, which could be seen in the relation between LCA node with SWM technology nodes (landfill, incineration, anaerobic digestion, recycling, and composting) through a municipal solid waste node. MFA node is linked with other keywords such as phosphorous, nitrogen, which both keywords directly related nutrient balance. This relationship of MFA and these substances consistence with the results of the interpretation of publication cluster attributes detected in the citation network (see Figure 2-6). The results of the co-words network also support the results of the modularity clustering analysis of the citation network, as well as the performing of text-mining technique to identify the main research theme of each cluster in the citation network.

2.3.6 Collaboration network

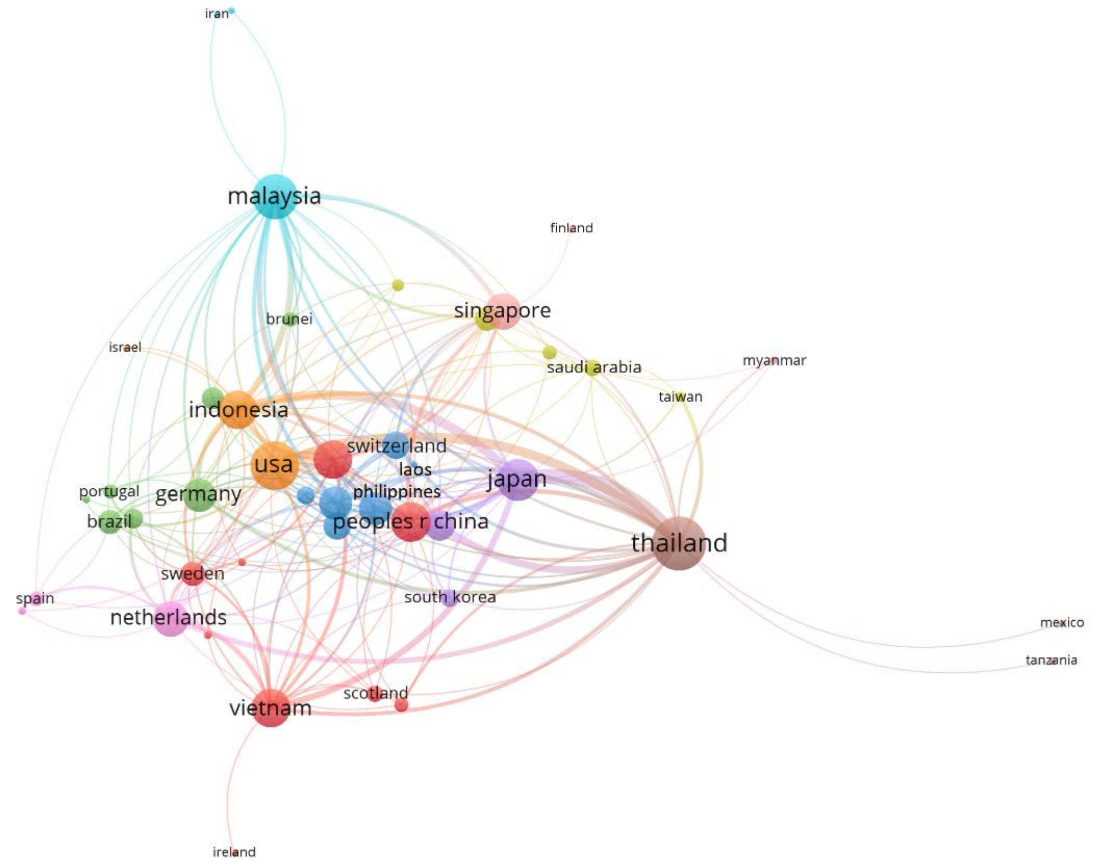


Figure 2-8 Collaborations network of IE research in ASEAN

I analyze the collaboration network of IE publications of ASEAN countries to investigate the potential supporting countries that could act as the main coordinator to establish the collaboration among member countries helping to fulfill the knowledge gaps in other ASEAN member countries. From the bibliometric results, Thailand is found as the leading countries in IE research in ASEAN, more specifically considering their expertise in LCA studies. From collaboration network, the results also show that Thailand has strong collaboration with countries outside ASEAN as well like Japan, USA, and the Netherlands, which support the advancement their LCA expertise (see Figure 2-8). The collaboration of other ASEAN countries also seems to have strong relations with institutions in Japan. Other developing countries in ASEAN such as Laos, Myanmar and Brunei have less international collaboration. The Philippines acts as the center for collaboration among ASEAN institutions and other countries.

2.4 Discussions

The results clearly show that the LCA is the most popular research area in the IE field in ASEAN countries. The LCA studies in ASEAN are centralized in the bioenergy production sector (biodiesel and bioethanol) from biomaterials which identical to the trends of LCA studies in the rest of the world (Li et al. 2018a; Zanghelini et al. 2016; Hou et al. 2015). In ASEAN LCA also employed to other sectors, for instance, investigating the environmental impacts in the energy consumption of residential buildings, as well as solid waste management.

LCA applications in ASEAN are not limited to these areas, it doses also includes LCA in other renewable energy sectors such as solar energy, wind, hydropower, thermal energy. But with further direction to combat with climate change, a better understanding of such renewable energy technologies would provide valuable information for promoting the renewable energy development. More LCA research related to these areas should be considered as the important area for future study.

In some ASEAN countries i.e. Indonesia, Philippines, Vietnam, and Laos, the mining sector play the crucial role in their economic development but comprehensive knowledge of its environmental consequence is limited, while the LCA framework have been employed to provides the information regarding the environmental consequences from mining industry in the rest of the world (Westfall et al. 2016; Ferreira and Leite 2015; Northey et al. 2014; Northey et al. 2013; Durucan et al. 2006). Transportation in most of

ASEAN countries is heavily relied on internal combustion engine vehicle. The trend of vehicle ownership is on the rise in ASEAN (IRENA 2018). Thus, LCA study of the electric vehicle could provide alternative information for decision making to shifting from fossil-based transportation to electricity-based transportation.

Agriculture products are important for ASEAN with total export of 106 billion USD in 2016 (34% of total export). The innovative agriculture systems might bring the co-benefit as increasing productivity, while at the same time reducing environmental impacts. LCA framework could be used as the measurement tools for such innovation.

LCA framework is popularly used for business strategy and products labeling in many developed countries to increase consumer perception of their products. From the results, there are several researches specifically dedicated to the application of LCA in product labelling (Mungkung et al. 2006; Ratnasingam et al. 2017; Tan et al. 2014). The research in this certain direction would help to enhance LCA knowledge-based in ASEAN.

More interestingly, the works related to Input-Output analysis were early used to study the economy of Philippines and Singapore back in 1971 and 1976 (Sicat 1971; Hsueh 1976). The IOT was largely applied to wider aspect ranging from investigating the economic impacts from certain economic sectors to investigating the environmental issue related to economic development. This is limited to some countries that have sufficient statistical data. But for countries like Brunei, Laos, Cambodia, Myanmar the IOT study is rare. This would require investment in both human resource and statistics data infrastructure, but as illustrated in many studies, the utilization of IOT could address numerous socioeconomic and environmental issues (Murakami et al. 2004; Yokoi et al. 2018; Wiedmann et al. 2013).

Material flow analysis studies in ASEAN, which is the core principle of IE, contribute to a trivial number of publications. The low number of MFA publications in ASEAN countries might cause by low awareness of the benefit of MFA usage (Aoki-Suzuki et al. 2012) and lack of statistical data that suitable for MFA. From the several studies that attempted to use national statistics for constructing the MFA, it shows that the data needed exists, but the data should be digitized from the available statistics and incorporated with some data refinement and estimation techniques (Vilaysouk et al. 2017, 2018). Recently in ASEAN, the most comprehensive material flow account using national statistics available for Laos (Vilaysouk et al. 2018), and Philippines (Martinico-Perez et al. 2018a). The comprehensive MFA provides information for a modern environmental policy that taken into consideration of resource efficiency. It could also provide the benchmark measure SDGs. These two available works of ASEAN countries could be seen as the regional example for other countries in conducting the comprehensive EW-MFA.

As in the coming decades, approximately 70% of the world population will live in the urban area, understanding the urban metabolism is important in order to deal with associate urban environmental challenges (Dijst et al. 2018). This also applied to ASEAN due to the fact that by 2050, about 66% of the total population will live in the cities (United Nations 2018). From the results, it indicates that the researches in UBM are quite trivial. In the coming years, it is important to realize that UBM will emerge and remain as the important tools in order to provide information for policy design to handle with the urbanization in ASEAN.

Considering all IE publications in ASEAN, MFA and UBM should be prioritized. Regarding the research related to the country boundary, Brunei, Cambodia, Laos and Myanmar, more researches are needed. More collaboration among ASEAN institution on IE research would help to boost the knowledge-based as well as reduce the redundancy of the works that relevant to each other. The institutes in Thailand show good performance of the research in LCA, while Singapore is expert on IOT. This offers opportunity for member countries to collaborate and exchange the knowledge to advance IE knowledge in the region.

2.5 Limitation of the study

The dataset used in this study was solitary obtained from WOS database. This might not cover all of the publications in IE, which one that not indexed in WOS database. Defining keywords for each IE discipline is difficult to cover all related terms, thus I only used the most common ones. Next limitation is the inconsistence bibliography format of cited documents in the publications' references, especially for the reference of the reports that manually created by authors. For example, I found that two of the big nodes in the citation network (see Figure 2-6) named differently as "[Anonymous], 2006, 14040 ISO" and "ISO, 2006 14040 ISO" but they actually refer to the same documents. These limitations should be considered in further research. The last limitation is that the publications that labeled with the country name in the dataset might not be the work from the institute in that certain country, but it might be only the work that related to that certain country as a case study.

2.6 Conclusion

This is the first time ever that all IE publications in ASEAN are analyzed to discover the evolution of IE in the region. I found that IOT has a long history since the first publication was published back in 1971. The LCA is the most popular research area in ASEAN and it has been exponentially increased since the mid-2000s. LCA researches mainly focus on renewable energy production from biomaterials, aquaculture, solid waste management technology and energy consumption in the building. In ASEAN, the IOT is mainly used to investigate the economic impacts from economic sectors, but also somehow including environmental perspectives, for instance, the climate change issues. MFA and UBM are slowly emerging and seeking for its position in the IE discipline in ASEAN. With the rapid rate of urbanization in ASEAN, IE knowledge-based related to urban system such as LCA for environmental-friendly products labelling, LCA of electric transportation systems, dynamic material flow analysis of ASEAN' cities would be the trends in the coming years. The need of understanding on other aspects such as LCA of mining and hydropower sectors are also important as these sectors strongly contribute to the economic development for low-income developing countries in the region. These are only some further researches summarizing from the review that awaiting the IE community to explore.

CHAPTER 3
Methodology: Improvement of EW-MFA framework for Developing Country

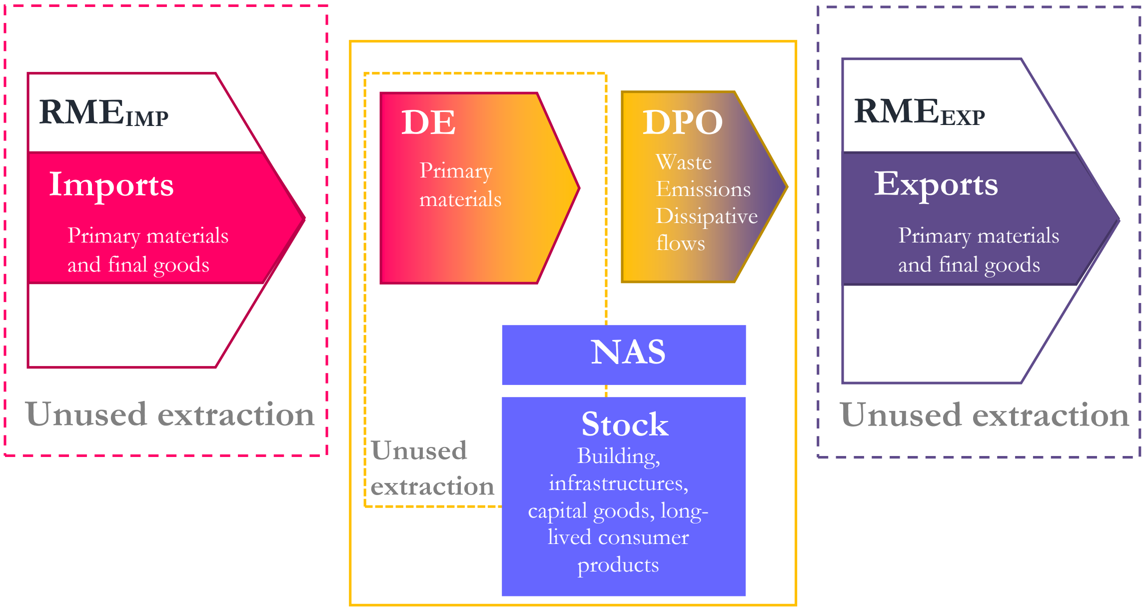
3.1 Eurostat EW-MFA compilation guideline

Economy-wide material flow analysis (EW-MFA) is an analytical framework to provide information on natural resource use for an economy. The European Statistics Office (Eurostat) played an important role in the development of the EW-MFA methodological guidelines. Eurostat's EW-MFA compilation guidelines have been widely used to compile EW-MFA at global, regional and national scales. The first EW-MFA methodological guideline published in 2001, prepared by a group of experts under Eurostat Task Force on Material Flow Accounting (Eurostat 2001). The first guideline presents a conceptual framework and practical guidance to establish the national material flow accounts.

Later in 2007, with better statistical data and experiences from the implementation of the first EW-MFA guideline, the guideline was updated and put more effort to harmonizing the framework to be consistency with the System of National Accounts and the United Nations System of Environmental and Economic Accounts (SEEA) (Eurostat 2007).

The Eurostat's Economy-wide MFA Compilation guide 2013 is the latest version of guideline that currently being used as the main framework for compiling EW-MFA for the national level (Martinico-Perez et al. 2018a; Vilaysouk et al. 2018) as well as global level (Schandl and Miatto 2018; Schandl et al. 2017).

The core principle of MFA is the first law of thermodynamics on the conservation of matter which stated that "… mass or energy, is neither created nor destroyed by any physical transformation process" (Eurostat 2001). This material balance principle provides indicators derived from given indicators by balancing all the flows within the studied system. MFA could be performed at many different level of aggregation for instance at firm/company level, specific economic sector, and national or regional level (Bringezu and Moriguchi 2002). The systematic Economy-wide material flow accounting framework is shown in Figure 3-1 below.



Source: adapted from UNEP (2016) and Eurostat (2001)

Note: RME_{IMP} is Imports in Raw Material Equivalent, DE is domestic extraction, NAS is net additions to stocks, Stocks is in-use of building, infrastructures, capital goods and long-lived consumer products, DPO is domestic processed outputs, RME_{EXP} is Exports in Raw Material Equivalent, unused extraction is movement of materials without further economic values

Figure 3-1 Economy wide-material flow accounting framework

3.2 Decoding Eurostat EW-MFA framework for developing country

In this section, Eurostat framework is introduced in detail with the potential limitations in applying to emerging economies. In many cases, Lao PDR will be used as an example of emerging economies, though the example for other countries will be included if available.

3.2.1 Domestic Extraction (DE)

Eurostat's EW-MFA guideline provides systematic procedures for compiling national MFA. The first step for EW-MFA compiling is the accounting of Domestic Extraction (DE). Materials inputs to socioeconomic systems extracted from the natural environment are considered as Domestic Extraction (DE) (Eurostat 2013). The Eurostat's guideline accounts only the materials that enter socioeconomic systems with economic-value. The unused domestic extraction is not accounted as EW-MFA indicators in this study. DE includes four major categories biomass, metal ores, non-metallic minerals, and fossil energy materials/carriers.

Biomass: Biomass category include organic non-fossil materials originated from biological mechanism (Eurostat 2013). Biomass could be disaggregated into 4-sub level A.1.1 crops, A.1.2 crops residues, A.1.3 Wood, and A1.4 Wild fish catch, aquatic plants/animal, hunting and gathering. Detail for materials included as DE of Biomass is shown in Table 3-1.

Table 3-1 Classification of DE for Biomass

A.1 Biomass
A.1.1 Crops (excluding fodder crops)
A.1.1.1 Cereals
A.1.1.2 Roots, tubers
A.1.1.3 Sugar crops
A.1.1.4 Pulses
A.1.1.5 Nuts
A.1.1.6 Oil-bearing crops
A.1.1.7 Vegetables
A.1.1.8 Fruits
A.1.1.9 Fibres
A.1.1.10 Other crops n.e.c.
A.1.2 Crop residues (used), fodder crops and grazed biomass
A.1.2.1 Crop residues (used)
A.1.2.1.1 Straw
A.1.2.1.2 Other crop residues (sugar and fodder beet leaves, other)
A.1.2.2 Fodder crops and grazed biomass
A.1.2.2.1 Fodder crops (incl. biomass harvest from grassland)
A.1.2.2.2 Grazed biomass
A.1.3 Wood
A.1.3.1 Timber (Industrial round wood)
A.1.3.2 Wood fuel and other extraction
A.1.4 Wild fish catch, aquatic plants/animals, hunting and gathering
A.1.4.1 Wild fish catch
A.1.4.2 All other aquatic animals and plants
A.1.4.3 Hunting and gathering

Source: Eurostat (2013)

Data for compiling (A.1.1) crops, (A1.3) Wood and (A1.4) Wild fish catch, aquatic plants/animals, hunting and gathering is usually well recorded in the statistics. The national agricultural, forestry and fishery statistics should be considered as the main data source for compiling. Another international data source which considered as the most consistent database is FAOSTAT provided by the United Nations Food and Agriculture Organization (FAO 2017). The FAOSTAT could be used to fill the data gaps when the national statistical data is missing.

For example, in the case of Lao PDR, data for (A.1.1) Crops was directly sourced from Agriculture statistics for the year 1988-2015 (Ministry of Agriculture and Forestry of Lao PDR 2015c). (A.1.3) Wood and (A.1.4) Wild fish catch, aquatic plants/animals, hunting and gathering are not recorded in the national statistics. Data from FAOSTAT is used to fill the data gap for (A.1.3) Wood, and the estimation of (A.1.4.1) Wild fish catch was made. According to results from various studies the quantity of sub-categories (A.1.4.2) All other aquatic animals and plants and (A.1.4.3) Hunting and gathering is relatively small, thus whenever the data is reported in the statistics, the accounting for these categories should be considered otherwise could be omitted from the compiling.

(A.1.2) Crop residues (used), fodder crops and grazed biomass category is one of the most uncertain part because is not commonly recorded in the statistics. In many studies, especially for developing countries, these materials are estimated from standard approach provided by Eurostat (Vilaysouk et al. 2018; Martinico-Perez et al. 2018b). Eurostat provides estimation approaches for (A.1.2.1) Crop residues (used) and (A.1.2.2) Fodder crops and grazed biomass.

There are three steps for estimation of (A.1.2.1) Crop residues (used) as following:

Step 1: Identification of crops which provide residues for further socio-economic use.

Step 2: Estimation of available crop residues via harvest factors

Available crop residues [t (as is weight)] = primary crop harvest [t (as is weight)] * harvest factor

Step 3: Estimation of fraction of used residues

Used crop-residues [t (as is weight)] = available crop-residues [t (as is weight)] * recovery rate

Harvest factors and recovery rates provided in Eurostat's guideline specifically refer to standard values for the most common crops residues used in Europe (Eurostat 2013). For developing countries, the adjustment of this factors should be made in order to reflect the local characteristics of agriculture systems in such countries.

(A.1.2.2.2) grazed biomass is usually poorly recorded in the agriculture statistics, at least for many developing countries. Two approaches are suggested in Eurostat's guideline when data could not be obtained directly from statistics, supply-side approach and demand-side approach. The most common approach used for estimate grazed biomass is the demand-side approach. The demand-side approach could be calculated from total animal feed requirement based on the number of livestock and feeding intake coefficient. Based on Eurostat's guideline, the estimation procedures are as follow:

Step 1: Calculate total roughage requirement

Roughage requirement = livestock [number] * annual feed intake [t per head and year]

Step 2: Calculate total demand for grazed biomass

Demand for grazed biomass = roughage requirement [t at 15% mc] - fodder crops incl. biomass harvest from grassland, A.1.2.2.1 [t at 15% mc] - industrial fodder products

<u>Metal ores:</u> This category of DE comprises two sub-categories (A.2.1) Iron and (A.2.2) Non-ferrous metal (see Table 3-2). In EW-MFA, metal ore is accounted as run-off-mine quantity (gross ore). The overburden is not accounted for in DE accounting. The mining statistics or national statistics yearbook contains the production data for important metal. Generally, in mining statistics, the non-ferrous metal group is reported whether in metal content or concentrate, therefore the conversion from such reported forms to gross ore has to be carried out. Eurostat suggests using average ore grades to convert metal content or concentrate back to total gross ore. The general conversion factors between metal content, ore concentrate and gross ore are provided in the guideline (Eurostat 2013). Metal ore may often contain more than one single valuable metal element, thus allocation of gross ore to different recovered elements should also be needed. Eurostat (2013) provide a procedure to allocate total gross ore to coupled metal products by using average commodity price.

$$gross\ ores_i = total\ ores\ processed_j * \frac{vm_i}{\sum_{i=1}^{n} vm_i}$$

Table 3-2 Classification of DE for Metal Ores

A.2 Metal ores (gross ores)
A.2.1 Iron
A.2.2 Non-ferrous metal
A.2.2.1 Copper
M.2.2.1 Copper ores - metal content
A.2.2.2 Nickel
M.2.2.2 Nickel - metal content
A.2.2.3 Lead
M.2.2.3 Lead - metal content
A.2.2.4 Zinc
M.2.2.4 Zinc - metal content
A.2.2.5 Tin
M.2.2.5 Tin - metal content
A.2.2.6 Gold, silver, platinum and other precious metals
A.2.2.7 Bauxite and other aluminium
A.2.2.8 Uranium and thorium
A.2.2.9 Other n.e.c.

Source: Eurostat (2013)

Non-metallic minerals: this category is the most dominant materials in the total DE for many developing countries, contribute to approximately 30% to 50% of total DE in recent years (Martinico-Perez et al. 2018b; Vilaysouk et al. 2017; Schandl et al. 2017). The classification of non-metallic minerals is given in Table 3-3.

Out of total 10 sub-categories of non-metallic minerals, sand, gravel, and clay are the majority. These materials are mainly used for construction purpose and catching more attention from the research community due to the unprecedented increasing within recent decades (Miatto et al. 2017; Schandl et al. 2017). Even these materials contribute to most part of domestic extraction but they are likely to be missing from statistics records (Fischer-Kowalski et al. 2011; Eurostat 2013).

Table 3-3 Classification of DE for Non-metallic minerals

A.3 Non-metallic minerals
A.3.1 Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone (excluding slate)
A.3.2 Chalk and dolomite
A.3.3 Slate
A.3.4 Chemical and fertilizer minerals
A.3.5 Salt
A.3.6 Limestone and gypsum
A.3.7 Clays and kaolin
A.3.8 Sand and gravel
A.3.9 Other n.e.c
A.3.10 Excavated earthen materials (including soil), only if used

Source: Eurostat (2013)

The potential statistics sources for compiling non-metallic minerals could be available in mining statistics, industrial production statistics, geological survey, or even from industrial associations reports (Eurostat 2013). But it is not the case for developing countries where statistical data is rare. For the case of Lao PDR, important non-metallic materials for industry sector could be sourced from Industrial Processing Statistics (Ministry of Industry and Commerce of Lao PDR 2015b). However, the number for limestone and gypsum, sand and gravel, and clay seems to be under-reported, thus the estimation is needed. Eurostat (2013) provides estimation techniques for estimating limestone, sand and gravel, and clays. The guideline suggests to compare the data recorded in the statistics and estimated values and employ the bigger number for compiling. Following are procedures for estimating such materials.

- Estimation of Limestone for cement production:

Limestone for cement production [t] = cement production [t] * 1.19

- Estimation of clays for brick production:

Clays for brick production [t] = brick production [m^3] * 0.988 [t/m^3]

Clays for roof bricks [t] = roof brick production [t] * 1.349

- Estimation of Sand and Gravel based on concrete production:

Sand and gravel [t] = Concrete production [t] * sand and gravel input in [%] / 100

- Estimation of Sand and Gravel based on concrete production:

Sand and gravel [t] = cement consumption [t] * 6.09

Which Cement consumption = cement production + cement imports - cement exports

- Estimation of sand and gravel for road construction

Sand and gravel [t] = length of new road [km] * material intensity [t/km]

- Estimation of sand and gravel for road maintenance

Sand and gravel [t] = total length of road [km] * material intensity for maintenance [t/km]

Fossil energy materials/carriers: Domestic extraction of materials in this category include both fossil energy materials/carriers in solid, liquid and gaseous forms. The classification of this category is shown in Table 3-4. (A.4.1) Coal and other solid energy materials/carriers are normally reported in energy statistics. Eurostat recommends referring to energy balance for compiling DE of fossil energy materials. For many developed countries, quality data of national energy balance is quite high and contains high details for even subcategory level (Eurostat 2013). For developing countries, this would not be the case. However, National Statistics Yearbook could provide, at least the production data for compiling these fossil materials (Martinico-Perez et al. 2018b; Vilaysouk et al. 2017). The international databases, for instance International Energy Agency (IEA) database, United Nations Industrial Commodity Production Statistics, the United States Geological Survey (USGS) and the British Geological Survey (BGS), could be used to fill the data gaps. For natural gas, it is generally reported in calorific units or in volume which the conversion to tonnes is required. The Eurostat's guide line provides conversion factors for such conversion.

Table 3-4 Classification of DE Compilation for Fossil energy materials/carriers

A.4	**Fossil energy materials/carriers**
A.4.1	**Coal and other solid energy materials/carriers**
A.4.1.1	Lignite (brown coal)
A.4.1.2	Hard coal
A.4.1.3	Oil shale and tar sands
A.4.1.4	Peat
A.4.2	**Liquid and gaseous energy materials/carriers**
A.4.2.1	Crude oil, condensate and natural gas liquids (NGL)
A.4.2.2	Natural gas

Source: Eurostat (2013)

3.2.2 Imports and Exports of material and products

Imports and Exports denote the integration of an economy into the world market for primary materials and its dependency on resource from abroad or its contribution to the global resource supply. The direct trade flows (in tonnes) at the time when commodities cross the national boundary is applied in EW-MFA. Based on Eurostat' guideline, the trade flows are grouped into main categories similarly to the classification of domestic extraction but with an additional category named (B.5) Other products (see Table 3-5). In Europe, waste, including hazardous and non-hazardous waste, could be transfer to different stages for final treatment or disposal based on Waste Shipment Regulation (WShipR), thus (B.6) Waste imported for final treatment and disposal is included in trade account.

Table 3-5 Classification of Imports and Exports

B.1	**Biomass and biomass products**
B.1.1	Crops, raw and processed
B.1.1.1	Cereals, raw and processed
B.1.1.2	Roots, tubers, raw and processed
B.1.1.3	Sugar crops, raw and processed
B.1.1.4	Pulses, raw and processed
B.1.1.5	Nuts, raw and processed
B.1.1.6	Oil-bearing crops, raw and processed
B.1.1.7	Vegetables, raw and processed
B.1.1.8	Fruits, raw and processed

B.1.1.9 Fibres, raw and processed
B.1.1.10 Other crops n.e.c., raw and processed
B.1.2 Crop residues and fodder crops
B.1.2.1 Crop residues (used), raw and processed
B.1.2.1.1 Straw
B.1.2.1.2 Other crop residues
B.1.2.2 Fodder crops
B.1.2.2.1 Fodder crops
B.1.3 Wood and wood products
B.1.3.1 Timber, raw and processed
B.1.3.2 Wood fuel and other extraction, raw and processed
B.1.4 Fish capture and other aquatic animals and plants, raw and processed
B.1.4.1 Fish capture
B.1.4.2 All other aquatic animals and plants
B.1.5 Live animals other than in 1.4., and animal products
B.1.5.1 Live animals other than in 1.4.
B.1.5.2 Meat and meat preparations
B.1.5.3 Dairy products, birds eggs, and honey
B.1.5.4 Other products from animals (animal fibres, skins, furs, leather etc.)
B.1.6 Products mainly from biomass
B.2 Metal ores and concentrates, raw and processed
B.2.1 Iron ores and concentrates, iron and steel, raw and processed
B.2.2 Non-ferrous metal ores and concentrates, raw and processed
B.2.2.1 Copper
B.2.2.2 Nickel
B.2.2.3 Lead
B.2.2.4 Zinc
B.2.2.5 Tin
B.2.2.6 Gold, silver, platinum and other precious metal
B.2.2.7 Bauxite and other aluminium
B.2.2.8 Uranium and thorium
B.2.2.9 Other n.e.c.
B.2.3 Products mainly from metals
B.3 Non-metallic minerals, raw and processed
B.3.1 Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone (excluding slate)

B.3.2	Chalk and dolomite
B.3.3	Slate
B.3.4	Chemical and fertilizer minerals
B.3.5	Salt
B.3.6	Limestone and gypsum
B.3.7	Clays and kaolin
B.3.8	Sand and gravel
B.3.9	Other n.e.c.
B.3.10	*Excavated earthen materials (including soil), only if used*
B.3.11	Products mainly from non metallic minerals
B.4	**Fossil energy materials/carriers, raw and processed**
B.4.1	Coal and other solid energy products, raw and processed
B.4.1.1	Lignite (brown coal)
B.4.1.2	Hard coal
B.4.1.3	Oil shale and tar sands
B.4.1.4	Peat
B.4.2	Liquid and gaseous energy products, raw and processed
B.4.2.1	Crude oil, condensate and natural gas liquids (NGL)
B.4.2.2	Natural gas
B.4.2.3	Adjustment for residence principle: Fuel bunkered by resident units abroad
B.4.2.3.1	Fuel for land transport
B.4.2.3.2	Fuel for water transport
B.4.2.3.3	Fuel for air transport
B.4.3	Products mainly from fossil energy products
B.5	**Other products**
B.6	**Waste imported for final treatment and disposal**

Source: Eurostat (2013)

In Europe, imports and exports are recorded in monetary and physical units in COMEXT database. This database is constructed based on Combined Nomenclature (CN8), which 6-digits code consistent with the Harmonized Commodity Description and Coding System (HS). This help EU member states easily established their trades account based on such harmonized code systems.

In developing countries, trades statistics is in the infancy stage. Only important products might be well reported in both monetary and physical units, but details at the subcategories level, which is required to allocate the materials into the main category, might be missing. This applies to the cases of Lao PDR and the Philippines (Vilaysouk et al. 2017; Martinico-Perez et al. 2018b). For the case of Lao PDR, the trades figure in national statistics yearbook cover important goods, 19 principal imported goods, and 7 principle exported goods, for year 1975 to 2004. Since 2005, imports and exports have been reported by commodities class based on ASEAN Harmonized Tariff Nomenclature code at 2-digits level in monetary unit and physical weight is missing. In order to convert the monetary value to physical weight, Eurostat refers to use tonne prices for such conversion.

The United Nations Commodity Trade Statistics database (UN Comtrade) has long history recoding trades transactions of more than 200 countries worldwide. In case of the trade data is missing in the national statistics, UN Comtrade could be used to fill the data gaps. However, about 20% of total records in the UN Comtrade database do not include physical weight (Dittrich and Bringezu 2010). In this case, tonne price could be used to estimate physical weight of such commodities. When using tonne price to convert trades in the monetary unit to physical weight, the consideration of variation of the unit price for finished or semi-finished goods should be taken into consideration. This concept yields lower uncertainty when applied to bulk primary materials due to lower variation in price. In physical trades account, the primary material is more likely contribute to the majority of the trade. It is suggested that when the estimation of the physical weight is needed, the priority should be first given for bulk primary materials.

After the physical weight could be obtained, it is needed to be converted to fit into MFA material categories. In order to match CN code or HS code to MFA material categories, Eurostat (2013) provides tables in Annex 3 of the guideline. This includes more than 20,000 individual commodities at 8-digits level matching to 6 main categories shown in Table 3-5.

3.2.3 Domestic Processed Output (DPO)

Domestic processed output (DPO) is the important MFA indicators in the output side, measuring environmental pressure from activities happened in the socioeconomic system's boundary. It contains 5 major categories including (F.1.) Emission to air, (F.2.) Waste landfilled, (F.3) Emission to water, (F.4.) Dissipative use of products, (F.5.)

Dissipative losses (Eurostat 2013). The DPO indicators firstly introduced in the comparative MFA study of five nations Germany, Japan, Austria, Netherlands, and the United States (Matthews et al. 2000). Since then in developing countries, only a few studies included this indicator in their EW-MFA study (Vilaysouk et al. 2018; Martinico-Perez et al. 2018a).

Table 3-6 Classification of DPO

F.1. Emissions to air
F.1.1. Carbon dioxide (CO_2)
F.1.2. Methane
F.1.3. Dinitrogen oxide (N2O)
F.1.4. Nitrous oxides (NOx)
F.1.5. Hydroflourcarbons (HFCs)
F.1.6. Perflourocarbons (PFCs)
F.1.7. Sulfur hexaflouride
F.1.8. Carbon monoxide (CO)
F.1.9. Non-methane volatile organic compounds (NMVOC)
F.1.10. Sulfur dioxide (SO2)
F.1.11. Ammonia (NH3)
F.1.12. Heavy metals
F.1.13. Persistent organic pollutants POPs
F.1.14. Particles (e.g. PM10, Dust)
F.1.15. Other (e.g. Nitrogen trifluoride - NF3)
F.2. Waste Disposal
F.2.1. Disposal of municipal waste to environment
F.3. Emissions to Water
F.4. Dissipative use of products
F.5. Dissipative losses

Source: (Eurostat 2016)

In 2016, Eurostat published a specific guideline for compiling DPO and Balancing items in order to provide the harmonized guideline to complete the comprehensive EW-MFA. For emissions to air, Eurostat (2016) suggests using data from air emission accounts and air emission inventories. Unfortunately, in developing countries, such accountings are rarely existing. Currently, the accounting for emissions to air, both in developed and developing countries (Schandl and Miatto 2018; Martinico-Perez et al. 2018a; Vilaysouk et al. 2018), are generally based on these international databases (UNFCCC 2018; European Commission 2016).

In Eurostat's guideline, (F.2.) Waste disposal is accounted for only the waste that discharged to the environment. Waste disposed of on the controlled landfill is not considered on EU's EW-MFA. However, Schandl and Miatto (2018) argue that all waste generated, in extraction, production, consumption processes, within the socioeconomic systems should be treated as part of DPO in the EW-MFA to avoid missing flows of waste component in the DPO. Several studies also treated waste disposal to landfill as part of DPO (Martinico-Perez et al. 2018a; Vilaysouk et al. 2018; Kovanda 2017).

Emissions to water is a very small flow in total DPO. Kovanda (2017)'s results show that the sharing of emissions to water is less than 1% of total DPO for the whole period studied. Eurostat (2016) suggests following the environmental reports as the reference for compiling this subcategory. In Europe, the data for Germany is available in the European Pollutant Release and Transfer Register. Due to a minor fraction, this subcategory could be ignored but due to the toxicity and associated negative ecosystem and health impacts, ones the accounting excluding this flow the notice should be mentioned. There are several studies focusing on these specific substances (Jiang et al. 2019; Antikainen et al. 2005; Cooper and Carliell-Marquet 2013; Cordell et al. 2013). This information could be integrated into the DPO accounting case-by-case if the flow is significantly importance regarding mentioned problems. For other two subcategories of DPO, Dissipative use of products and Dissipative losses, these two data are rarely exit and difficult to quantify. Eurostat (2016) suggests to include these flows only when data available or could be obtained with justifiable effort.

3.2.4 Derived Indicators, Balancing Items and their accounting rules

The derived EW-MFA indicators considered in this study are indicators calculated from the material flow balancing principle of the EW-MFA model, including direct material input (DMI), domestic material consumption (DMC), and last but not least NAS. Following is the explanation of the indicators and the calculation rules as seen in Table 3-7.

Table 3-7 EW-MFA and its accounting rules

Indicator name	Abbreviation	Accounting identity
Domestic Extraction	DE	
Imports	IMP	
Balancing items for inputs	BI_{in}	
Direct material input	DMI	DMI = DE + IMP
Domestic Material Consumption	DMC	DMC = DE + IMP - EXP
Domestic Processed Output	DPO	
Exports	EXP	
Balancing items for outputs	BI_{out}	
Net Addition to Stocks	NAS	NAS = DE + IMP + BI_{in} – DPO – EXP - BI_{out}
Physical Trade Balance	*PTB*	PTB = IMP - EXP

DMI is developed to quantify total direct material input to an economic system. DMI accounts only for materials that have economic value, thus does not include balancing items and unused domestic extraction.

The DMC indicator measures apparent consumption of materials in a defined economic system. As mentioned in Eurostat (2001), the term consumption is not defined as final consumption but instead actual consumption in the economic system as a whole. DMC is calculated as the sum of all material extraction domestically and total imports including raw materials, semi-raw materials, and finished products.

NAS is the indicator that measures the growth of physical stocks in a society (Eurostat 2001). The consumption of energy and materials during the lifetime and end-of-life disposal processes of a product makes the NAS indicator one of the most important indicators in many industrialized countries (Krausmann et al. 2017). NAS can be calculated directly from gross additions to stocks, minus removals of stocks, or can be indirectly calculated from balancing inputs and outputs with appropriate balancing items (Eurostat 2016, 2001). In this study, due to limitations in the data, I calculated NAS indirectly from inputs and outputs following a material balancing approach.

Balancing items, as the name implies, is the additional indicator in EW-MFA for balancing materials on the input and output sides. Generally, these indicators are reported in specific tables and are not included in the accounting of MFA aggregate indicators (Eurostat 2016). Balancing items are important when the NAS is calculated as the balancing of inputs and outputs. Balancing items are required both on the inputs and outputs sides.

Balancing items for inputs (BI_{in}) consist of oxygen for combustion processes and respiration of humans and livestock, nitrogen for the Haber-Bosch process, and water requirements for the domestic production of exported beverages. In this study, only oxygen for the combustion processes and respiration of humans and livestock were accounted for BI_{in}. Balancing items for outputs (BI_{out}) were calculated for the amount of water vapor from combustion of energy carriers, gases, and vapor from humans and livestock respiration. BI_{in} and BI_{out} were estimated mainly based on the coefficients provided in the guidelines (Eurostat 2016).

3.2.5 Summarize data sources and estimation approaches for compiling EW-MFA

Table 3-8 presented all of the indicators required for compiling full balance EW-MFA. The potential data sources for each indicator and materials are summarized. The estimation approaches to estimate the missing data in the statistics also briefly explain. The details of the improved methodologies proposed in this study that used to estimate such missing data are shown as the section number in the bracket.

Table 3-8 Summary of data sources and estimation approaches for compiling EW-MFA

Indicators	Materials	Data Source	Estimation Approach	Remark
DE	A.1. Biomass			
	A.1.1 Crops	Agriculture, forestry, and fishery statistics; FAOSTAT		
	A.1.2 Crop residues (used), fodder crops and grazed biomass		Harvest and recovery factors Feeding intake (3.3.1)	Using primary crops data from A.1.1 Use total livestock number with feeding intake
	A.1.3 Wood	Agriculture, forestry, and fishery statistics FAOSTAT		Conversion from volume to physical weight
	A.1.4 Wild harvest			Including in the account when data available
	A.2. Metal ores			
	A.2.1 Iron	Mining statistics; Individual mining company reports;	Conversion from metal content or concentrate to gross ore; direct accounting (3.3.3)	
	A.2.2 Non-ferrous metal			

		British Geological Survey (BSG); United States Geological Survey (USGS)		
	A.3. Non-metallic minerals			
	A.3.1. Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone (excluding slate)	Mining statistics, Industrial production statistics, Individual mining company reports, British Geological Survey (BSG), United States Geological Survey (USGS)		
	A.3.2. Chalk and dolomite			
	A3.3. Slate			
	A3.4. Chemical and fertilizer minerals			

Indicators	Materials	Data Source	Estimation Approach	Remark
		Mining statistics, Industrial production statistics, Individual mining company reports, British Geological Survey (BSG),		
	A.3.5. Salt			
	A.3.6. Limestone and gypsum		Cement production	
	A.3.7. Clays and kaolin		Brick production	Based on coefficients provided by Miatto et al. (2017) and Eurostat (2013)
	A.3.8. Sand and gravel		Appearance consumption of cement and extension of infrastructure network (3.3.2)	Based on coefficient developed in this dissertation, supplemented by default values of Eurostat (2013)
	A.3.9. Other n.e.c.			

	A.3.10. Excavated earthen materials (including soil), only if used (optional reporting)	United States Geological Survey (USGS)		
	A.4. Fossil energy materials/carriers			
	A.4.1. Coal and other solid energy materials/carriers	National energy balance, International Energy Agency (IEA), British Geological Survey (BSG), United States Geological Survey (USGS)		
	A4.2. Liquid and gaseous energy materials/carriers			

Indicators	Materials	Data Source	Estimation Approach	Remark
Imports and Exports				
	B.1. Biomass and Biomass products	National Trades statistics, FAO database, UN Comtrade, International Energy Agency (IEA)	Estimate physical based on average tonnage price (3.4)	
	B.2. Metal ores and concentrates, raw and processed			
	B.3. Non-metallic minerals, raw and processed			
	B.4. Fossil energy materials/carriers, raw and processed			
	B.5. Other products			
	B.6. Waste imported for final treatment and disposal			
DPO				
	F.1. Emissions to air	Air emission accounts, UN		

Indicators	Materials	Data Source	Estimation Approach	Remark
		Framework Convention on Climate Change (UNFCCC), Emissions Database for Global Atmospheric Research (EDGAR), UNECE Convention on Long Range Transboundary Air Pollutants		
	F.2. Waste Disposal	Waste statistics	Estimate based on waste generation, waste management data (3.5)	
Indicators	Materials	Data Source	Estimation Approach	Remark
	F.3. Emissions to water			This category is small in mass, if the data is not available this could be ignored
	F.4. Dissipative use of products	International Fertilizer Industry Association, FAO database, UNFCCC		

F.5. Dissipative losses		Data for compiling this category have never been quantified. Eurostat (2016) suggests to include in the accounting only when data can be provided with a justifiable effort
Balancing Items		
G.1. Balancing items: input side	Estimate based on Eurostat's DPO compilation guideline	
G.1.1. Oxygen for combustion processes		
G.1.2. Oxygen for respiration of humans and livestock; bacterial respiration from solid waste and wastewater		
G.1.3. Nitrogen for Haber-Bosch process		
G.1.4. Water requirements for the domestic production of exported beverages		

Adapted from Eurostat (2013); (Eurostat 2016)

3.3 Improvement of DE accounting

3.3.1 Estimation of Fodder crops and Grazing biomass

As mentioned in the above section, the availability and reliability of the statistical data for fodder crops and grazing biomass is difficult for compiling DE of biomass in many developing countries. The standard default values provided in Eurostat's guideline is suitable and applicable for countries that share similarity in agriculture operation with European countries. Krausmann et al. (2013) provide more comprehensive harvest factor and recovery rate for eight global regions which could reflect more suitable parameters based on geological and agriculture systems in such certain region. Using regional factor is more suitable than applying the factor specifically developed for European countries.

In this dissertation, the improvement of the estimation of crops residues used for developing countries is tried and assessed by integrating the local data from national statistics, for example, the crops that potentially have the residues to be further used in other economic activities with the harvest factors and recovery rates provided in Table 3-9 and Table 3-10.

Table 3-9 Harvest factors for estimation of crops residues

	E. Asia	*S. and C. Asia*	*N. Africa and W. Asia*	*Sub-Saharan Africa*	*Latin America*	*N. America and Oceania*	*W. Europe*	*E. Europe*
Wheat, other cereals	1.5	1.7	1.5	2.3	1.5	1.2	1.0	1.5
Rice, Paddy	1.0	1.5	1.2	1.5	1.2	1.2	1.2	1.2
Maize	3.0	3.5	3.0	3.5	3.0	1.2	1.2	1.9
Millet	3.0	3.5	3.0	3.5	3.0	1.2	1.2	1.9
Sorghum	3.0	3.5	3.0	3.5	3.0	1.2	1.2	1.9
Roots and Tubers	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Sugar Cane	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Sugar Beets	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Pulses	0.4	0.4	0.4	0.4	0.4	1.0	1.0	1.0
Soybeans	1.2	1.5	1.5	1.5	1.5	1.2	1.2	1.5
Groundnuts in Shell	1.2	1.5	1.5	1.5	1.5	1.2	1.2	1.2
Rapeseed, oil crops	2.3	2.3	2.3	2.3	2.3	1.9	1.9	1.9

Source: Krausmann et al. (2013) and Wirsenius (2003)

Table 3-10 Recovery rate for estimation of crops residues

	E. Asia	S. and C. Asia	N. Africa and W. Asia	Sub-Saharan Africa	Latin America	N. America and Oceania	W. Europe	E. Europe
Cereals, including rice and maize	0.8	0.9	0.8	0.9	0.8	0.7	0.7	0.75
Roots and tubers	0.75	0.75	0.75	0.75	0.75	0	0	0.25
Sugar cane	0.52	0.52	0.47	0.47	0.4	0.47	0.47	0.47
Sugar Beets	0.75	0.75	0.75	0.75	0.75	0	0	0.25
Sugar crops	0.8	0.8	0.8	0.8	0.8	0	0	0.3
Bean, Dry	0.5	0.5	0.5	0.5	0.5	0	0	0.5
Other pulse	0.8	0.9	0.8	0.9	0.8	0.7	0.7	0.75
Other oil crops	0.8	0.9	0.8	0.9	0.8	0.7	0.7	0.75
Sunflower seed	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Rape seed	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7

Source: Krausmann et al. (2013) and Wirsenius (2003)

For the grazing biomass, the improvement for estimation was done by introducing the new feeding intake co-efficient for different livestock based on the local data. The calculation process was following the estimation process provided in the Eurostat's guidelines. The new indicators were calculated based on the information obtained during the data collection. The technical information was provided from (Ministry of Agriculture and Forestry of Lao PDR 2015a, 2015b). The feeding intake was classified into five main livestock categories, buffalo, cattle, pig, goat and sheep, and poultry. The details for feeding intake factors are shown in Table 3-11.

Table 3-11 Animal feeding intake for estimation of grazing biomass

Livestock	Feeding intake (This study) (tonnes/year)	Feeding Intake (Eurostat) (tonnes/year)*
Buffalo	7.7	4.5
Cattle	5.5	
Sheep and goats	0.9	0.5
Horses	-	3.7
Poultry	0.1	-

Source: * Eurostat (2013)

3.3.2 Material intensity of sand and gravel used in concrete production

The sand and gravel are important materials in total volumetric quantity of the total DE. However, due to its low values and dominant in earth crush, this material category is usually missing in the statistics or underreported (Miatto et al. 2017). Many studies (Krausmann et al. 2014; Krausmann et al. 2008) employed a simplistic estimation approach provided by Eurostat (2013). Miatto et al. (2017) improved the estimation approach for non-metallic minerals taken into account technological complexity and civil engineering knowledge, and this improved approach have been employed to update the global resource use account (Krausmann et al. 2017; Schandl et al. 2017) as well as county-level study (Martinico-Perez et al. 2018a; Martinico-Perez et al. 2018b). Based on the conceptual idea, the material intensity of sand and gravel for estimation from cement consumption is specifically developed for developing country, based on concrete mixing design of Lao PDR.

The total sand and gravel required to produce concrete based on cement consumption is calculated using concrete mixing ratios ($C_{(i)}$: cement (kg) / $S_{(i)}$: sand (liter) / $G_{(i)}$: gravel (liter)). The standard mixing ratio for Lao PDR was provided by the Department of Housing, Ministry of Public Works and Transportation of Lao PDR. There are four standard mixing ratios (Concr.1: 150/400/800; Concr.2: 250/400/800/; Concr.3: 300/400/800; Concr.4: 350/400/800) classified by the strength of the concrete (the higher the cement ratio, the higher the strength of the concrete). The four possible mixing ratios were calculated and the shares of Concr.1: 1/2.67/5.33 to Concr.4: 1/1.14/2.29 in Lao concrete consumption. Then the intensity of sand and gravel used in Lao PDR from cement consumption was calculated as:

$$\lambda_{concr.Lao(i)} = \frac{S_{(i)}}{C_{(i)}} * \rho_{sand} + \frac{G_{(i)}}{C_{(i)}} * \rho_{gravel} \qquad \text{(EQ. 3-1)}$$

Where $\lambda_{concr.Lao(i)}$ is the intensity of concrete, $S_{(i)}$ is the ratio of sand, $C_{(i)}$ is the ratio of cement, $G_{(i)}$ is the ratio of gravel, and ρ_{sand} and ρ_{gravel} are the density of sand and gravel, respectively.

From the above equation (EQ. 3-1), the calculation of intensity of concrete resulted in a range between $\lambda_{concr.Lao(4)} = 5.77$ to $\lambda_{concr.Lao(1)} = 13.46$. High strength concrete (Concr.3 and Concr.4) is mainly used for reinforced concrete, which is used for building structural elements and floors. I assume that high strength concrete Concr.4 accounted for 60% of total use, followed by Concr.3 at 30%, and low strength concrete Concr.2 and Concr.1 accounted for 5% each. The resulting material density for sand and gravel based on cement consumption for Lao PDR is 6.55 tonnes of sand and gravel ($\lambda_{concrete.Lao(aver.)} = 6.55$) per tonne of cement. This number is higher than the global average estimated by Miatto et al. (2017) ($\lambda_{concr} = 5.26$) and a default number provided by Eurostat as 6.09 which is explained by differences in mixing ratio standards and assumptions made in the estimation process. The comparison for material intensity of sand and gravel used per cement consumption from this study and other two studies is shown below (Table 3-12).

Table 3-12 Comparison of material intensity for estimation of sand and gravel

$\boldsymbol{\lambda_{concr}}$	**Values**
This study	6.55
Eurostat (2013)	6.09
Miatto et al. (2017)	5.26

The total sand and gravel required to produce concrete based on cement consumption is calculated as equation below:

Sand and Gravel for concrete production = $\boldsymbol{\lambda_{concr}} * Cement\ Consumption$ (EQ. 3-2)

3.3.3 Direct accounting for metal ores based on commercial database

In 2015, domestic extraction of metal ores of extractive nations, for instance Chile, Australia, accounts for more than 50% of total DE of their nations (UNEP IRP 2018b). But in most EW-MFA previous studies, metal ores were estimated based on conversion factors back from metal content or metal concentrate to gross ores. This approach involved high uncertainty regarding to high variation of ore grades. Accounting DE of metal ores using data directly obtained from site specific data is recommended in order to avoid uncertainty in calculating gross ores. In this dissertation, direct accounting approach was applied using the operation data that reported by mining company. One source that include extensive information of the mining industry is the S&P Global Market Intelligence database (SNL). SNL database is a platform that provides financial news, data and analysis for financial services, real estate, energy, media, communication and the metal and mining sectors. The SNL database includes detailed information about the mining sector such as information on exploration budgets, resource and reserves, as well as production information. In this study total ore processed data for individual mines were used to compile domestic extraction data for non-ferrous metals. From the total processed ore data, allocation of the coupled products was performed using "Aliquot allocation of ore tonnages" based on long-term average prices of the metal (Eurostat 2013). For other non-ferrous metals, which the amount is small, the concentrate and metal content products and average ore grades from Eurostat are used to calculate the total gross ores.

3.4 Improvement of Import-Export accounting

Trade accounting, as mentioned earlier, is a difficult accounting for developing countries when the trades statistics is not available or available but with only the monetary unit. UN Comtrade database could be used to fill the data gaps, however about 20% of the trades data in UN Comtrade have no quantity (Dittrich and Bringezu 2010) and even higher for the developing countries at more than 34% for the case of Lao PDR, 24% for Bangladesh.

In this dissertation, the improvement of trades accounting for developing countries has been conducted based the statistical data integration of national statistics and international database. Lao PDR is chosen as the case study for showing how the difficulty of trades accounting for EW-MFA in developing countries could be done when the statistical data is poor.

Trade statistics in Lao PDR are in their infancy. The full and reliable trade statistics is only available for the year 2015. Additionally, national trade data from the Ministry of Industry and Commerce of Lao PDR covers the years 2010 to 2015 but only in monetary unit (Ministry of Industry and Commerce of Lao PDR (2015a)). To compile consistent trade accounts, the integration of national statistics with information from the UN COMTRADE (2017) database is inevitable. For those years where no reporting exists in Lao national statistics dataset, the bilateral trade from Lao PDR's trade partners, such as Thailand and Viet Nam which have more reliable trade statistics, are used. For the countries with less reliable trade statistics, it is sometimes useful to obtain data from bilateral trade counterparts with more reliable dataset. The national dataset (2010–2015) and UN Comtrade data (1988–2015) were used which required numerous data adjustments.

Data from the Ministry of Industry and Commerce of Lao PDR (2015a) contains transaction data on imports and exports for trade values for 2010 to 2015 but reports physical trade only for 2015. The "tonne price" was estimated for all commodities individually for year 2015 based on HS-code classification at 4-digit level. Then results of unit prices were applied to monetary values in other years (2010–2014) to estimate the physical weight.

This approach yields unrealistic unit prices for some commodities such as cement and crude oil because of potentially false records of total weight. This was discovered when comparing national data with UN Comtrade data and such irregularities were corrected through data matching technique. This strategy was employed for the top 20 commodities in terms of physical unit, for both imports and exports, to establish adjusted unit prices for those commodities. These "adjusted unit price" were used to align UN Comtrade data and national trade data into one coherent time series.

3.5 Estimation of Domestic Processed Output (DPO)

Data for compiling DPO is rarely exist in developing countries. This is also true for the Lao PDR. In this dissertation, compiling DPO for developing countries is demonstrated based on the case study of Lao PDR. To homogeneously compile EW-MFA based on the mass-balancing principle of MFA, DPO should be derived or calculated based on the inputs flows and releasing of waste the end of life stage of in-use stocks. For the important component of DPO such as waste from mining sector, in the case study, this was calculated based on the indigenous data of the model. Due to the data availability, waste to landfill and emissions to air were sourced from exogenous sources.

For the air emission inventory in Lao PDR, only the first and second national air emissions inventories reported to the UN Framework Convention on Climate Change are available (Ministry of Natural Resources and Environment of Lao PDR 2000, 2013). The national statistics on air emissions in Lao PDR are not sufficient to construct the time series data, thus I decided to source the data from the Emission Database for Global Atmospheric Research version 4.3.2 provided by European Commission (2016) for the accounting of emissions to air. The database includes time series data for CO2 emissions from 1970 to 2015, and for other greenhouse gases (GHGs) from 1970 to 2008. In this accounting, regarding the defined system boundary, I excluded emissions from short life cycle biomass burning, large-scale biomass burning, carbon emissions/removals of land-use, and land-use change and forestry were not included inside the system boundary. The accounting distinguishes 19 specific gases. CO_2 data was directly sourced from the database for the whole period but other gases during 2010–2015 were extrapolated from 38 years of historical trends available in the database.

Besides emissions to air, waste disposal issues are becoming common challenges for many developing countries including Lao PDR. In EW-MFA, waste disposal figures are aggregated from municipal solid waste (MSW) and industrial waste. In Lao PDR, there is no MSW database yet, although waste generation rates in recent years are available for some major cities such as Vientiane (Babel and Vilaysouk 2015), Luang Prabang (Vilaysouk and Babel 2017), Savannakhet, and Champasak (Sang-Arun and Pasomsouk 2012), as well as for the country level (Ngoc and Schnitzer 2009) with figures ranging from 0.55 to 0.7 kg per capita·day. Based on these MSW generation rates, I assumed that the generation rate was 0.55 kg per capita·day for 1988 to 2001 (Ngoc and Schnitzer 2009), and 0.67 kg per capita·day from 2002 to 2015 (Babel and Vilaysouk 2015; Vilaysouk and Babel 2017; Sang-Arun and Pasomsouk 2012).

Industrial waste refers to undesired outputs from manufacturing processes at factories as well as at mining sites. The amount of industrial waste is strongly related to the level of industrialization. Based on industrial processing statistics, the main industry in Lao PDR from 1988 to the late 1990s was food processing, while large-scale mining activities took place from 2003 onwards. In Lao PDR, industrial waste data is not available. Khanal and Souksavath (2005) reported that waste from industries and markets accounted for 19.1% of total waste generated in Vientiane. Based on this percentage and the total waste generated in Vientiane in 2012 (Babel and Vilaysouk 2015), industrial waste in Vientiane was estimated to be 44,175 tonnes per year, or 60.4 kg per capita·day. This industrial waste generation rate was used to estimate total industrial waste generated from manufacturing in this study.

Another huge industrial waste in Lao PDR is mining waste. Lao PDR started a large-scale commercial mining industry in 2003 (Sepon mine in Savannakhet Province). Based on the S&P Global Market Intelligence database (SNL), there are more than fifteen active mining projects (including copper, gold, potash, platinum, alumina, bauxite, phosphate, lanthanides), and four of them are operating (SNL 2017). Total gross ores processed and commodity production are recoded in the SNL database. I calculated the mining waste simply by subtracting total commodity products from total ores processed.

Dissipative use of products includes inorganic and organic fertilizer such as manure, compost, sewage sludge, and pesticides. The first accounting for dissipative flows in MFA was carried out by Matthews et al. (2000) for Japan, Austria, Germany, and the Netherlands. The systematic accounting for dissipative use of products in Eurostat (2016) consists of organic fertilizer, mineral fertilizer, sewage sludge, compost, pesticides, seeds, salt, other thawing materials spread on roads, solvents, laughing gas and other. In Lao PDR, agricultural inputs, especially pesticides and chemical fertilizers, are relatively low and imported from neighboring countries (Somsak Kethongsa 2005). In the accounting, I accounted for organic fertilizer (animal manure) by estimating based on daily manure production coefficients. I used the manure production rate of the smallest cattle size in Queensland (Department of Agriculture and Fisheries: The State of Queensland 2017) as it is similar to the average size of cattle in Lao PDR, based on the its weight. For other small animals, including pigs, goats and sheep, and poultry, I used the default coefficients provided by Eurostat (2016). Chemical and mineral fertilizers and pesticides are mainly imported, thus I accounted for these materials based on import data from the trade dataset.

3.6 Uncertainty assessment of EW-MFA results

3.6.1 Monte Carlo Simulation

Uncertainty commonly exists in MFA due to the nature of the data used in the accounting, for instance various data sources, different measurement methods, and the quality of the data itself (Laner et al. 2014). Rechberger et al. (2014) stated that "…MFA should now enter into an era where reporting uncertainty ranges of stocks and flows is mandatory …". Laner and colleagues published several papers reviewing the literature on applied uncertainty in MFA studies, and Monte Carlo simulation (MCS) was suggested as one systematic approach to handle the uncertainty in MFA (Laner et al. 2016; Laner et al. 2014, 2015). Considering the many improvements in this study still have uncertainty, assessing the uncertainty will be essential.

Some recent studies have incorporated uncertainty analysis. Krausmann et al. (2017) employed MCS in their global dynamic stocks model to propagate uncertainty of their results by assuming uncertainty ranges for some parameters (for instance material inputs, mean of lifetime, recycling and down-cycling fraction) and the authors suggested performing a sensitivity analysis to check for systematic errors in the assumed parameters.

Patrício et al. (2015) used the data imputation method and error propagation techniques to quantify the uncertainty of a regional MFA study.

Generally, the dataset for compiling EW-MFA in developing countries is not completely available, and forces us to estimate and make a lot of assumptions. In this study, due to concerns about the quality of official statistics and estimated data used in the model, MCS was performed to test the robustness of the model results. Another benefit of including uncertainty analysis in national MFA is that it can inform practitioners at the country level which indicators influence the uncertainty of the results and need to be carefully checked before performing the accounting. MFA results with plausible ranges also help users in making decisions when using the indicators. The systematic step of the calculation is shown in section 4 of the supporting information.

MCS was run one thousand times simultaneously for the entire MFA model to obtain the uncertainty (standard deviation(σ)) of DMI, DMC, and NAS. In order to perform MCS, first we need to specify the distribution of the uncertain parameter, and the mean (μ) and standard deviation (σ) must be known in the case of normal distribution (Rechberger et al. 2014). In this study, the model input data is treated as the mean of the normal distribution and uncertainty ranges were assumed for each indicator (except for uncertainty of imports and exports) as explained in the following paragraphs.

The uncertainty range of MFA indicators in this study was assumed following common practices in MFA when uncertainty data is not available (Patrício et al. 2015; Krausmann et al. 2017; Kovanda et al. 2008). I attribute uncertainty ranges to the indicators based on their sources. Data gathered from official statistics was considered to be good and ±10% was chosen as the uncertainty range, while data obtained from estimation was considered to have higher uncertainty with ±30% (uncertainty of DE). DPO and balancing items were almost completely estimated based on available information (except mining waste). The uncertainty ranges chosen for these indicators was based on the numbers suggested in literature (±15%) (Patrício et al. 2015; Kovanda et al. 2008; Krausmann et al. 2017). For imports and exports, I calculated the uncertainty directly based on the trade dataset. Details of the assumed approach for the uncertainty range of DE are shown in Table 3-13. I assumed that the uncertainty remains constant all the year in the observed period. The uncertainties at sub-category level were propagated using Gauss's law of error propagation (EQ. 3-3).

$$\sigma_{DE}(\mathrm{t}) = \sqrt{\sigma_{crops}(t)^2 + \sigma_{crop\ residues}(t)^2 + \cdots + \sigma_{coal}(t)^2} \qquad \text{(EQ. 3-3)}$$

Table 3-13 Assumption of uncertainty for DE at subcategory level

Material	Sub-category	Data source	Uncertainty Range (%)
Biomass			
	Crops	1	± 10%
	Crops residues	2	± 30%
	Grazing and fodder crops	2	± 30%
	Wood and timber	3	± 10%
Metal			
	Ferrous metal	1	± 10%
	Non-ferrous	3	± 10%
Non-metallic		1,2	± 30%
Fossil		1	± 10%

Note: [1]Lao national statistics, [2]estimated based on coefficients, [3]international statistics

Imports and Exports data used in this accounting were calculated using the conversion approach to convert the monetary value into physical weight and considered containing some uncertainty. The details for the conversion were discussed in (Vilaysouk et al. 2017). I calculated the uncertainty for imports and exports using confidence interval approach. From the "tonne price" of every transaction, I grouped this calculated "tonne price" into the same group of the product based on HS-Code. From the group of "tonne price" of the same product, mean of "tonne price" ($\hat{\mu}_i$) was calculated. In the trade dataset used in this study, there are about five thousand products at HS-Code 8-digits level. However, some of the products contained few transactions. For example, in the import data set, airplane spare parts imported to Lao PDR in 2015 contained less than 50 transactions and the price were extremely different among them. Thus, I filtered the products that have the transaction less than 100 transactions per year and excluded from the standard deviation calculation. The uncertainty for different products was calculated using confidence interval with 95% confidence level (EQ. 3-4). I then calculated the uncertainty of imports by combining the standard deviation of all products using Gauss's law of error propagation (EQ. 3-5). For the exports, the same concept was applied. From the calculation, uncertainty for imports in 2015 was ± 13%, and ± 10% for exports. Due to the insignificant amount of imports and exports in the past decade, I assumed that the uncertainty for imports and exports are the same for the observed period.

$$\sigma_i = \frac{\left[\left(\hat{\mu}_i - Z_{\frac{\alpha}{2}} * \frac{\hat{\sigma}_i}{\sqrt{n_i}}\right) + \left(\hat{\mu}_i + Z_{\frac{\alpha}{2}} * \frac{\hat{\sigma}_i}{\sqrt{n_i}}\right)\right]}{2 * 1.96} \quad \text{(EQ. 3-4)}$$

$$\sigma_{imp} = \sqrt{{\sigma_1}^2 + {\sigma_2}^2 + \cdots + {\sigma_n}^2} \quad \text{(EQ. 3-5)}$$

After preparing all the data required for MCS, the MCS is performed to generate a set of random values of DE, IMP, EXP, DPO, and balancing items using mean values and the uncertainty ranges given. After that, the aggregated MFA indicators (DMI, DMC, and NAS) were calculated following an equation modified from the Eurostat compilation guidelines as follows:

$$DMI_c^{mc}(t) = IMP_c^{mc}(t) + DE_c^{mc}(t) \quad \text{(EQ. 3-6)}$$

where mc denote "mc_{th}" run in MCS and year t respectively, and c means the cohort.

The mean value of the cohort of DMI at year t was calculated as:

$$\overline{DMI}_{\bar{c}}(t) = \frac{1}{n} \sum_{i=mc}^{n} DMI_c^{mc}(t) \quad \text{(EQ. 3-7)}$$

As mentioned earlier, the uncertainty ranges of aggregated MFA indicators in this study were assumed as the standard deviation of the normal distribution. The uncertainty of DMI ($\sigma_{DMI}(t)$) was calculated using EQ. 3-8.

$$\sigma_{DMI}(t) = \pm \sqrt{\frac{1}{n} \sum_{i=mc}^{n} (DMI_c^{mc}(t) - \overline{DMI}_{\bar{c}}(t))^2} \quad \text{(EQ. 3-8)}$$

The calculation of DM_c^{mc} is as follows:

$$DMC_c^{mc}(t) = IMP_c^{mc}(t) + DE_c^{mc}(t) - EXP_c^{mc}(t) \quad \text{(EQ. 3-9)}$$

where $DMC_c^{mc}(t)$ is domestic material consumption of MCS mc at year t, $IMP_c^{mc}(t)$ is imports of MCS at year t, $DE_c^{mc}(t)$ is domestic extraction of MCS at year t, $EXP_c^{mc}(t)$ is exports of MCS at year t, and cohort c=t.

Average value of DMc at year t than calculated as:

$$\overline{DMC}_{\bar{c}}(t) = \frac{1}{n}\sum_{i=mc}^{n} DMC_c^{mc}(t) \qquad \text{(EQ. 3-10)}$$

Uncertainty of DMC at year t could be obtained by:

$$\sigma_{DMC}(t) = \pm\sqrt{\frac{1}{n}\sum_{i=mc}^{n}(DMC_c^{mc}(t) - \overline{DMC}_{\bar{c}}(t))} \qquad \text{(EQ. 3-11)}$$

The NAS indicator is calculated mainly based on other indicators. The calculation was performed by EQ. 3-10.

$$NAS_c^{mc}(t) = IMP_c^{mc}(t) + DE_c^{mc}(t) + {BI_{in}}_c^{mc}(t) - {BI_{out}}_c^{mc}(t) - DPO_c^{mc}(t) - EXP_c^{mc}(t)$$

(EQ. 3-12)

where ${BI_{in}}_c^{mc}(t)$ *and* ${BI_{out}}_c^{mc}(t)$ are balancing items on the inputs side and outputs side of MCS at year t, and cohort c=t.

Average value of NAS at year t than calculated as:

$$\overline{NAS}_{\bar{c}}(t) = \frac{1}{n}\sum_{i=mc}^{n} NAS_c^{mc}(t) \qquad \text{(EQ. 3-13)}$$

Uncertainty of NAS at year t could be obtained by:

$$\sigma_{NAS}(t) = \pm\sqrt{\frac{1}{n}\sum_{i=mc}^{n}(NAS_c^{mc}(t) - \overline{NAS}_{\bar{c}}(t))} \qquad \text{(EQ. 3-14)}$$

3.6.2 Gaussian Error Propagations

In MFA study, another straightforward to handle the uncertainty of model results is Gaussian's error propagation law (Brunner and Rechberger 2003). The MFA indicators are treated as the mean of normal distribution and assumed to be independent from each other. The uncertainties of indicators needed to be known. The uncertainties are then propagated following the Gaussian Error propagation's law. The uncertainty of indicators derived from EW-MFA are evaluated by following equations:

$$\sigma_{DMC}(t) = \pm\sqrt{\sigma_{DE}^2 + \sigma_{IMP}^2 + \sigma_{EXP}^2} \qquad \text{(EQ. 3-15)}$$

$$\sigma_{DMI}(t) = \pm\sqrt{\sigma_{DE}^2 + \sigma_{IMP}^2} \qquad \text{(EQ. 3-16)}$$

$$\sigma_{NAS}(t) = \pm\sqrt{\sigma_{DE}^2 + \sigma_{IMP}^2 + \sigma_{EXP}^2 + \sigma_{BL\,in}^2 + \sigma_{BL\,out}^2 + \sigma_{DPO}^2} \qquad \text{(EQ. 3-17)}$$

Due to the generic principle of MFA which is the linear combinations of indicators in the inputs side and outputs side, the uncertainty of DMC, DMI, and NAS obtained from this approach, theoretically is quite similar to ones obtained from Monte Carlo

Simulation. In this case, these two approaches could be used interchangeably depend on the availability of the data such as the complexity of the model, the uncertainty level of model inputs data, for instance. The justification for choosing the method to evaluate the robustness of the MFA results is not limited to these two approaches mentioned hereby. The discussions for handling uncertainty in MFA were discussed in more details in these literatures (Patrício et al. 2015; Laner et al. 2016; Laner et al. 2014, 2015; Rechberger et al. 2014).

CHAPTER 4
A Case Study: Comprehensive EW-MFA of Developing Economies, Lao PDR

4.1 Background

The Lao People's Democratic Republic (Lao PDR or Laos) is a land-locked country located in the center of the Indochinese peninsula, with a small population of 6.4 million and a very low population density of 27 persons per km^2 (Lao Statistics Bureau 2015b). Over the past decade the Lao economy has grown strongly, with the annual Gross Domestic Product (GDP) growth rate consistently over 7%. Per-capita GDP increased from 324 US$ to 1,818 US$ between 2000 and 2015 (World Bank 2017b) but Lao PDR is still considered to be one of the least developed countries in Asia. Lao PDR is rich in natural resource including metal ores, fossil fuels, timber, non-timber forest products and hydroelectricity. The structural composition of the Lao economy has shifted from agriculture to industry and services since the economic liberalization of 1986. The proportion of GDP generated by the agriculture sector shrank from 52.1% to 23.8% over the period 2000 to 2015 (Lao Statistics Bureau 2015a).

Fast growing resource extraction, energy production and population growth, as well as an increase in domestic resource consumption caused a recent escalation of environmental problems in Lao PDR. These new environmental issues of pollution and waste have created new challenges for policymakers. Environmental policy in Lao PDR, despite its lack of capacity, needs to deal with the speed and magnitude of increasing natural resource extraction, increased air pollution, growing municipal solid waste and toxic waste from industries, the fast accumulation of materials in buildings and infrastructure (in-use stocks), and climate change. The paucity of information on the sheer magnitude of primary material extraction, waste flows and emissions presents a profound limitation for policymakers in Lao PDR trying to address and manage the new environmental challenges. Presenting a full set of material flow accounting indicators is a way to strengthen the knowledge base of the policy community. It could allow for integrated policies that simultaneously address economic growth and the mitigation of environmental pressures and impacts.

Due to steady development in Lao PDR over the past decade, the structure and level of resource use will have changed. Now it is time for Lao PDR to update its resource use knowledge, and provide information for policymakers to integrate results of this study into the national development strategy. Lao PDR has just started to build up significant infrastructure to support its economic development. The need to catch up with its neighbors in urbanization and industrialization and to improve the material standard of living of its people will require a massive amount of materials. Appropriate policies to support sustainable resource management and resource efficiency are necessary in Lao PDR's development planning.

The first comprehensive MFA dataset for the Lao PDR, as well as the first such study for a lower middle-income country in the Asia-Pacific region would contributes to a better understanding of the feasibility and current limitations of preparing EW-MFA in developing countries, and reveals the influence of data quality on the uncertainty of MFA results. The evidence-base information about the relationship between material use, growth in material stocks, waste and emissions, and the role of trade would assist policymakers to establish socioeconomic development policies to guide development in the Lao PDR toward a sustainable pathway. Integrating sustainable resource use into economic development could enable Lao PDR to identify strategies to increase the country's competitiveness, and achieve the aspired economic benefits at lower environmental cost.

4.2 Domestic Extraction (DE)

The results show that domestic extraction of Lao PDR increased from 11.3 million tonnes in 1988 to 120.1 million tonnes in 2015, a ten-fold increase in less than three decades (see Table 4-1.a). Initially, the domestic extraction of biomass dominated total DE at a share of almost 80%, reflecting the agricultural nature of the Lao economy. Starting in the early 1990s, non-metallic minerals, mainly aggregates for road construction, started to play a bigger role in DE and consistently increased until the 2000s. Domestic extraction accelerated in 2003–2004 when the first commercial gold mine in Sepon started to operate, which resulted in a sharp increase in metal ores in total DE. In 2005, there was a notable increase in non-metallic minerals, which was caused by the coincidence of a number of very large construction activities including the start of construction of the biggest hydropower plant in Lao PDR, Nam Theun 2. This enormous hydroelectricity dam has a total installed capacity of 1,070 MW and is one of the largest in the region. Nam Theun 2 was accompanied by a number of other medium-sized hydropower projects with total capacity of more than 1,000 MW.

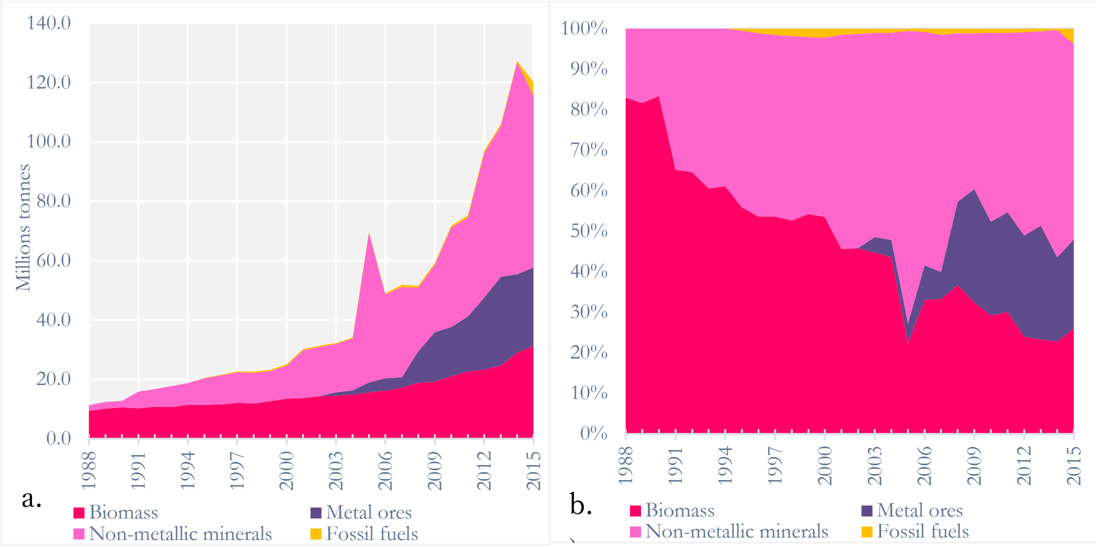


Figure 4-1.a. Domestic extraction by four materials categories and b. shares of total DE in percentage in 1988–2015

2005 was also the start of large-scale copper mining (Sepon Mine, Savannakhet Province). Until 2008, all material extraction, except for metal ores, grew slowly but 2005 marked the starting point of a very rapid increase in extraction of copper and gold ores destined to shore up export earnings. Throughout the period, the DE of fossil fuels was minor due to the lack of deposits of oil and natural gas. There are, however, significant coal deposits in many locations across the country with the biggest deposit being Hongsa lignite deposit located in Xayabury Province. Domestic coal was partially supplied for the cement industry and the surplus was exported. In 2015, the first Lao coal power plant, Hongsa Power in Xayabury Province with a total power output of 1,653 MW, started operation. It requires a steady input of domestic coal and will drive coal extraction. Until now, the amount of fossil extraction has remained insignificant compared to other material categories but this is going to change in the future. By 2015, non-metallic minerals accounted for almost half of DE, followed by 26% biomass, 22% metal ores, and 4% fossil fuels (see Table 4-1.b). This reflects massive changes in the Lao economy over the past three decades, from a purely agricultural, biomass-based economy to a growing focus on mining, energy generation and creating transport corridors between Thailand, Viet Nam and the Chinese Yunnan province.

Table 4-1 shows DE by 13 sub-categories. The total average growth rate of DE was 9%. Non-ferrous metal ores experienced the most rapid growth at 45% per year, on average, but staring from a very low base in 1988. Iron ores and chemical and fertilizer minerals also increased steadily with an average yearly growth of 25% and 29%, respectively. Construction materials such as limestone and gypsum, clay and kaolin, and sand and gravel, which have the highest share in DE, increased at a slower rate of around 13% to 17% per year. Crops, important for food supply, animal feed and fiber grew at an intriguing rate of 9% per year on average which was much faster than the world average of 4% per annum. This very substantial expansion of agricultural production is testament to the ongoing transition of Lao agriculture from a smallholder subsistence system to a modern, higher input industrialized agricultural system. Fossil fuels are also seeing substantial yearly increases but future growth is expected to be much larger in light of the fuel needs of an expanding conventional power generation infrastructure.

Table 4-1 Domestic extraction by sub-categories, in tonnes

DE in Sub-categories	*1988*	*1998*	*2008*	*2015*	*Annual Growth rate (1988 to 2015)*
Crops	1,475,277	2,251,159	6,293,993	13,885,152	9%
Crop residues and fodder and grazed biomass	3,878,456	5,239,760	8,034,022	10,557,586	4%
Wood	3,795,135	4,086,783	4,175,680	6,285,279	2%
Fish capture and other aquatic animals	269,413	347,093	406,254	457,096	2%
Iron	-	-	13,693	247,461	25%
Non-ferrous metal	1,097	2,379	10,587,887	26,248,442	45%
Chalk and dolomite	91,500	794,000	1,725,000	3,974,710	15%
Chemical and fertilizer minerals	-	5,500	1,000	391,748	29%
Salt	11,000	16,000	25,100	50,930	6%
Limestone and gypsum	80,000	579,948	2,013,589	5,775,030	17%
Clays and kaolin	80,436	283,115	1,408,694	3,105,213	14%
Sand and gravel	1,666,667	8,639,852	16,283,129	44,553,892	13%
Coal and other solid energy products	-	401,000	565,741	4,564,700	15%
Total	11,348,981	22,646,588	51,533,783	120,097,238	9%

4.3 Trades of materials in Lao PDR (IMP-EXP)

Figure 4-2 shows the trends in imports and exports in physical units in Lao PDR between 1988 and 2015. These results establish, for the first time, a realistic account of physical trade for the Lao economy achieved by aligning all available information from Lao National Statistics with international, UN COMTRADE, datasets. Overall, the physical trade accounts show an increasing engagement of the Lao economy with the rest of the world. In the 1990s imports were very small at 0.1 to 0.9 million tonnes, reflecting the effects of import substitution policies. The acceleration of imports started in 2003–2004 when imports started to increase from initially one million tonnes in 2003 to 7.5 million tonnes in 2015. Total imports in 2015, however, reached only 6% of domestic material input (DMI; the sum of DE and IMP). In 2015, the main imports were construction materials (mostly cement), fossil fuels, metal products such as iron and steel bars, and semi-manufactured and finished products and animal fodder (see Figure 4-2.a).

From the late 1980s to the late 1990s exports were dominated by timber, reaching a peak of 0.8 million tonnes in 1997. In 1997–1998, total exports from Lao PDR declined, due to economic contraction during the Asian financial crisis and diminished demand for Lao products from the country's Southeast Asian neighbors. By 2003, exports had recovered and refocused on hard coal and non-metallic minerals. Increasingly, with the production of gold and copper, metal ores have become more important in the Lao export portfolio. In 2011–2012 Lao exports experienced another slump, this time caused by sluggish global demand for primary resource in the aftermath of the global financial crisis of 2008–09 and the slow recovery of the world economy. Total exports fell from 3.1 million tonnes to 2.7 million tonnes. Since the year 2000, agricultural exports have started to shift from timber to crops. Exports of biomass from 2000 onwards were mainly led by the export of agriculture products, shifting from exports of timber to crop production (see Figure 4-2.b). The marked increase in imports and exports during the past decade indicates that the Lao economy has become more integrated into global markets. This has also caused greater vulnerability of the economy to global resource markets and price fluctuations, which is especially problematic for countries whose exports are dominated by primary materials because of an absence of industrial infrastructure and value-adding in the country.

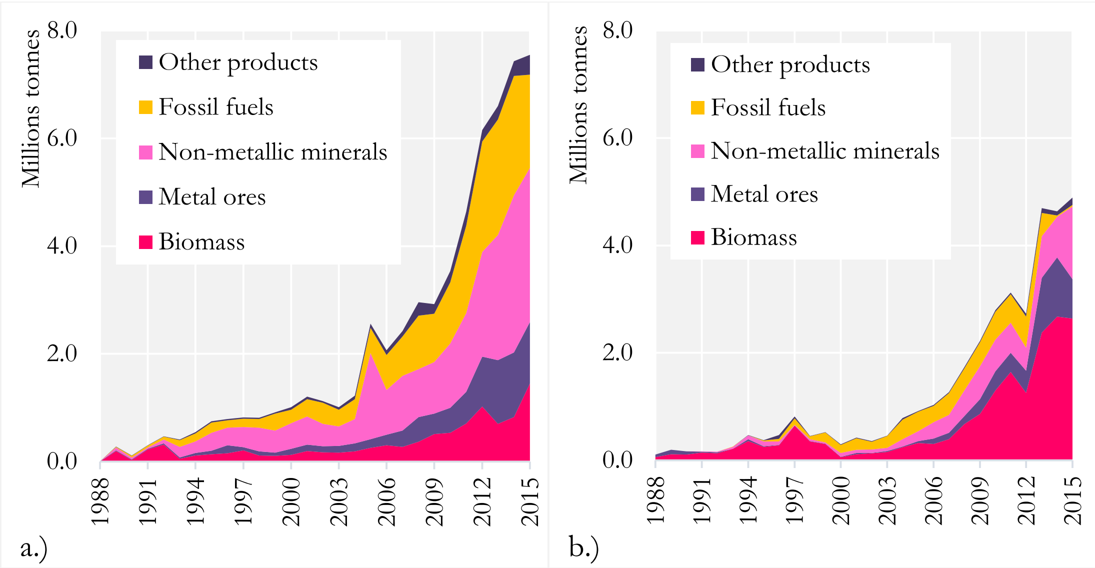


Figure 4-2. a. Imports by main materials categories, b. Exports by main materials categories in 1988–2015

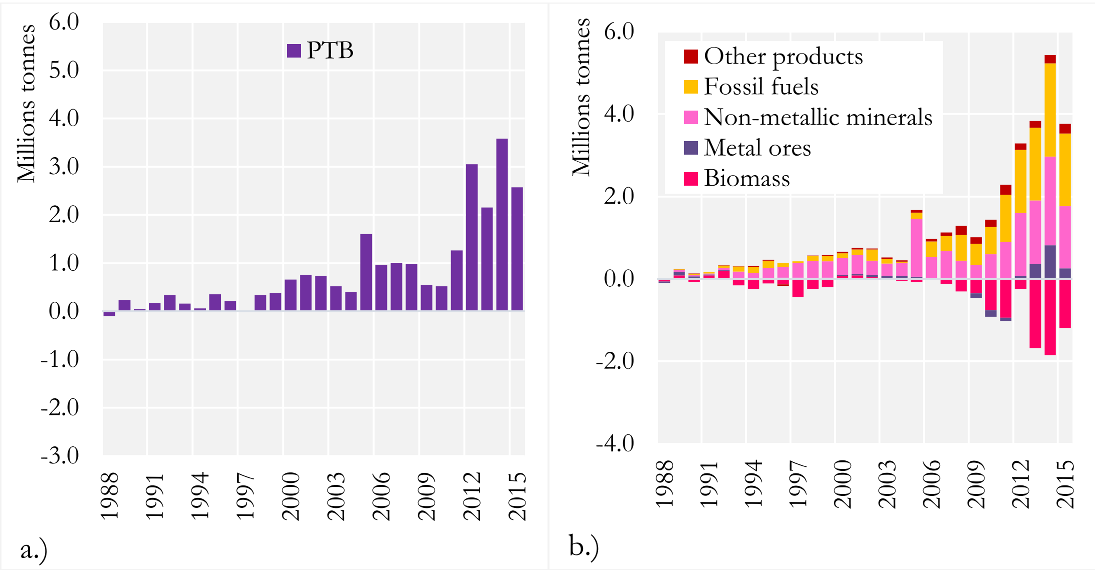


Figure 4-3. a. Total physical trade balance and b. Physical trade balance by main materials categories in 1988–2015

Despite the focus on primary sectors for export, the physical trade balance (PTB) for Lao PDR, i.e. imports minus exports, has been mostly in surplus showing Lao PDR as a net importer of materials (see Figure 4-3.a). Lao PDR has been a net importer of fossil and non-metallic minerals and exported surpluses of biomass, timber and more recently crops (Figure 4-3.b). From 2006 to 2011, the increase in copper production, with three copper mines now in operation, meant that Lao has become a net exporter of metal ores. A continuing focus on primary industries for export may mean that the physical trade balance of Lao PDR will become negative and Lao will become a net exporter of primary materials in the not very distant future.

4.4 Domestic Processed Output (DPO)

Domestic processed output (DPO) reflects the fast-increasing resource-base of the Lao economy. DPO in Lao PDR remained constant at less than six million tonnes for more than two decades and started to grow around 2006 (see Figure 4-4). The structure of DPO is characteristic of the economic development path of Lao PDR. Since the start of the mining boom in Lao PDR, massive amounts of waste rock and mine tailings have accumulated at mine sites (MW), reaching 70% of DPO by 2015. DPO in 2015 was 41.1 million tonnes, of which more than 74% was from industrial sectors, followed by 15% of emissions to air (EM), 7% of organic material, mineral fertilizers and pesticides (DSP), and 4% of municipal solid waste (MSW) (see Figure 4-4.b). The structure of DPO is perhaps atypical compared to other developing countries, and mining-related flows are a potential source of large and long-lasting environmental issues (Koide et al. 2012).

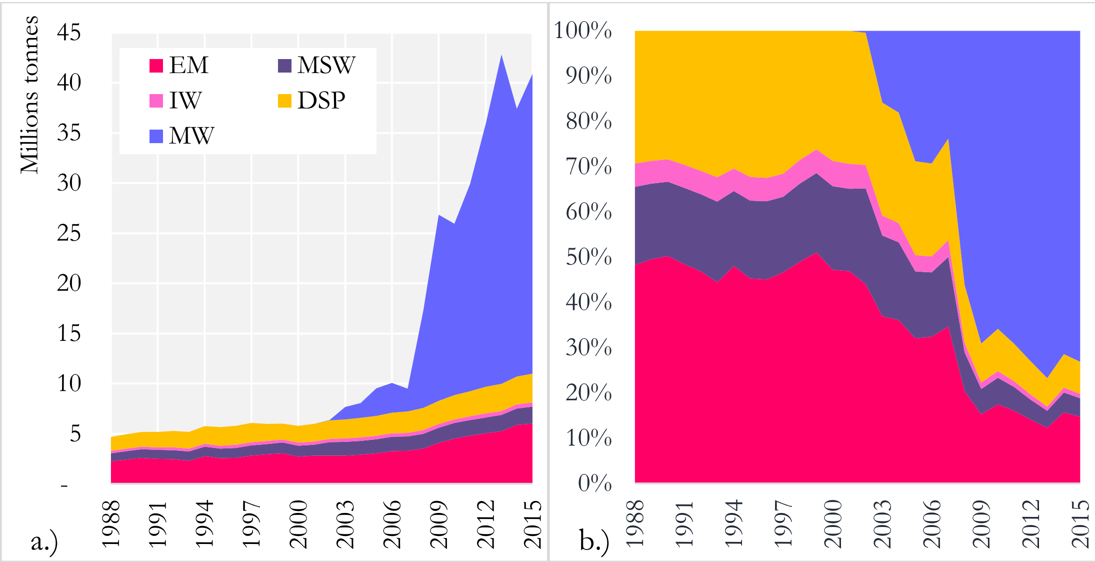


Figure 4-4 Domestic Processed Output from Socioeconomic systems of Lao PDR 1998 – 2015 a.) in million tonnes, b.) sharing in percentage; note: EM-emission to air, DSP-dissipative use of products, MSW-Municipal solid waste, MW-mining waste, IW-industrial waste

4.5 Balancing items

The balancing items is important in EW-MFA when the full mass balance is aimed to be conducted. Balancing items is needed for both in the inputs side and outputs side. For instance, in the fossil energy carrier materials when combusted CO_2 is released back to environment as accounted in the DPO at the output side. To correctly balance the flows, O_2 required for the combustion should also be included in the input side. On the one hand, when energy carrier materials contain water. The water content released back to environment in terms of water vapor in the output side. Thus, the water vapor from combustion process need to be added as the balancing items in the output side.

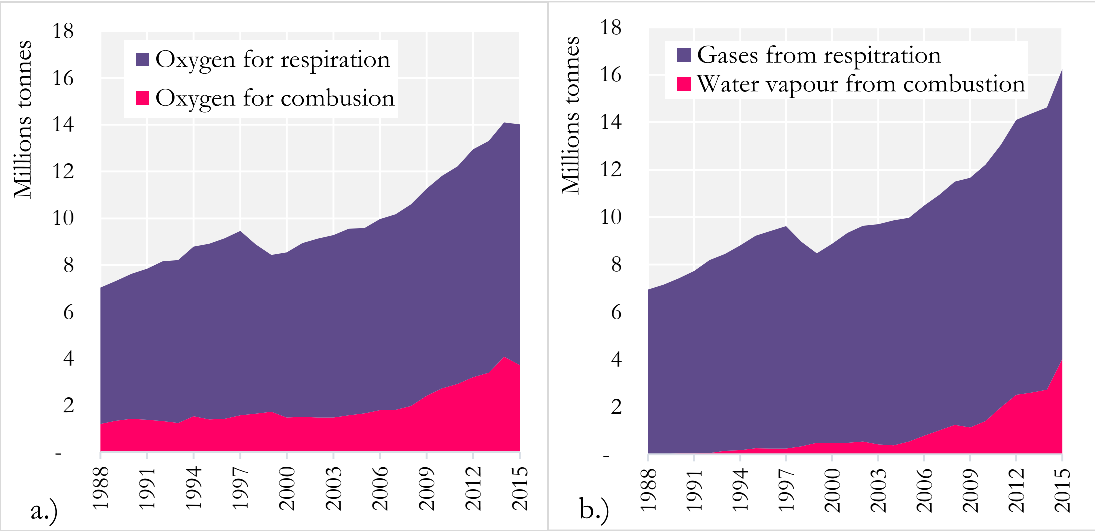


Figure 4-5 a) Balancing items at input side, b) Balancing items at output side

The balancing items in the input side comprise oxygen for fossil fuels combustion and human and livestock respiration. In some cases, nitrogen for Haber-Bosch process and water requirements for the domestic production of exported beverages are also included. This flow is important for conducting full mass balance and it normally ranges between 20% to 30% of total material input. In this study, for the balancing items in the input side mainly dominated by oxygen for human and livestock respiration (71% to 84% throughout the studied period, see Figure 4-5)). The oxygen required for fossil fuels combustion is relatively small due to low consumption of fossil fuels for energy which mainly substituted by wood fuels and hydroelectricity. This figure is opposite for the case of the industrial developed world, which oxygen for combustion is larger than oxygen for respiration.

Similarly, in the output side, gases from human and livestock respiration accounted for most part of the balancing items. During late 1980s to 1990s, the gases from respiration almost accounted for the rest of this flow. The balancing items in the output side in 2015 is about 16 million tonnes (about 24% of total outputs).

4.6 Direct Material Input (DMI) and Domestic Material Consumption (DMC)

Figure 4-6 shows historical direct materials input (DMI) and domestic material consumption (DMC) of Lao PDR since 1998 to 2015. DMI measures the direct material input into socioeconomic system from domestic environment, plus imported materials and products. Domestic material consumption (DMC) is the indicator measures the direct materials consumption within socioeconomic systems which calculated by subtracting the exports from DMI. Due to low volumes of trades activities in Laos, the figures for both DMI and DMC mirror the DE figure. From now on, DMC will be used as the main indicators for interpretation of materials consumption in Laos.

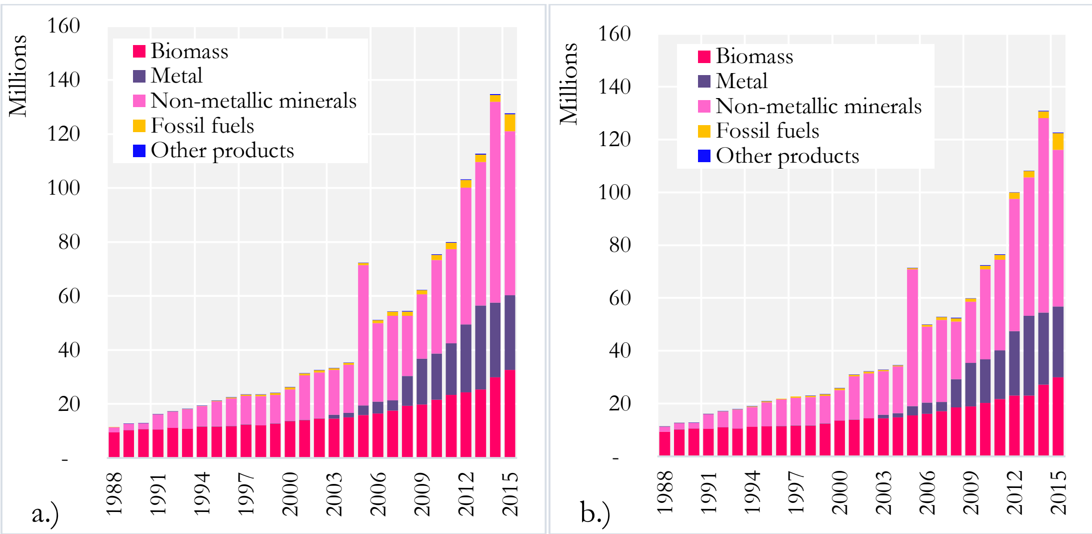


Figure 4-6 a)Direct Material Input (DMI), b) Domestic Material Consumption(DMC) from 1988 – 2015

In early years, the majority of DMI and DMC is biomass and very low, only about ten million tonnes. The rapid increasing of DMC started in 1990s leading by the increasing of non-metallic minerals which mainly provide materials for infrastructure development. The DMC of non-metallic minerals experienced the spike increase in 2005 which mainly driven by the massive consumption of concrete for mega project, hydropower plants, and another jump of non-metallic mineral in 2014 which was caused by the extension of road network. DMC of metals is mainly metal ores for mining industry. In Laos, the commercial mining of gold and copper started in 2003 and 2005, respectively. DMC of biomass is growing slowly with the average annual growth rate of 5%. From 1988 to 2015, total DMC increased by almost 11-fold, led by increasing of non-metallic minerals and metal ores.

4.7 Overall material flows and its uncertainty

Figure 4-7.a shows the full set of material flow accounting indicators for Lao PDR for the year 2000 at the onset of the mining and hydroelectricity growth and for the year 2015 to provide two snapshots of material use, waste and emissions of the Lao economy. The results include uncertainty ranges obtained from the Monte Carlo simulation.

In 2000, DE was 25.2±3.8 million tonnes and accounted for more than 72% of total inputs. Imports were negligible at that time. Balancing items on the input side include oxygen for combustion processes and oxygen for respiration of humans and livestock, but do not include nitrogen for the Haber-Bosch process or water requirements for the domestic production of exported beverages.

DPO in 2000 was 5.8±0.9 million tonnes, dominated by emissions to air and the dissipative use of products, i.e. chemical and organic fertilizers. Exports amounted to 0.3±0.1 million tonnes, which was relatively low compared to other indicators. Balancing items are important for the calculation of NAS. The outputs balance, including water from fossil fuels combustion and gases from respiration of humans and livestock, is high at 8.9±1.4 million tonnes. From the balancing of the MFA in 2000, NAS was 19.8±4.4 million tonnes. These materials have accumulated in society in the form of buildings, roads, infrastructure systems, and machinery, along with home appliances.

In 2015, all input indicators increased significantly. DE grew close to five-fold to 120.4±18.6 million tonnes (see Figure 4-7.b). Imports grew to 7.5±1.0 million tonnes. On the output side DPO increased massively, caused by mining sector extraction and associated waste flows, and was at 40.9±6.3 million tonnes. As discussed above, the majority of DPO in 2015 was industrial and mining waste, followed by emissions to air, dissipative use of products, and municipal solid waste. Exports also increased rapidly, more than 16-fold compared to the year 2000, illustrating the growing role of products from Lao PDR in international commodity markets. About half of all material inputs accumulated in societal stocks, as indicated by a 4-fold growth of NAS at 79.8±20.0 million tonnes. Uncertainty ranges increased in line with growing material throughput.

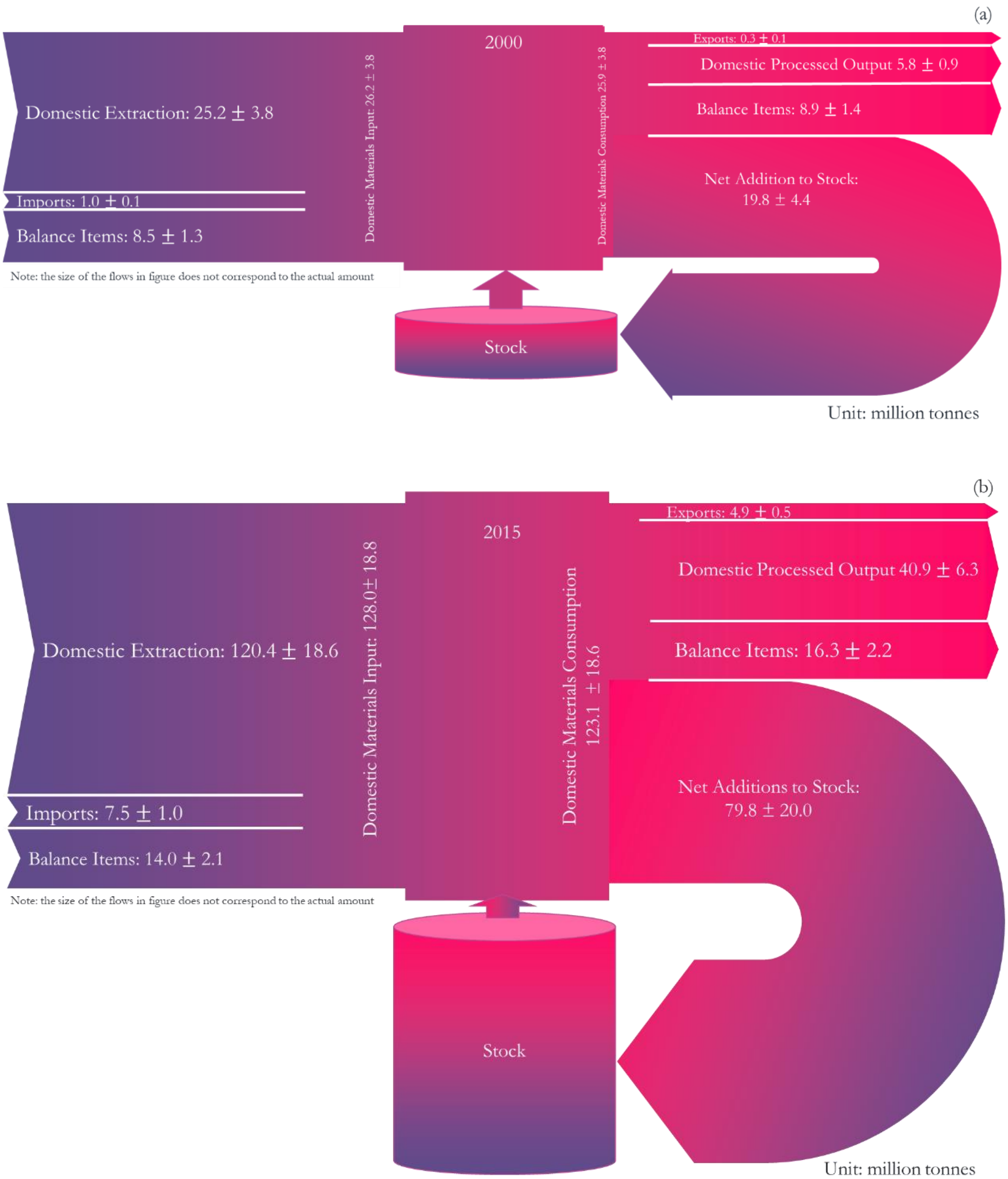


Figure 4-7 EW- MFA of Lao PDR in 2000, 2015

4.8 Uncertainty of EW-MFA derived indicators

The quality of MFA results depends on the quality of primary inputs data and appropriate estimation approaches being used in estimating unavailable data. In this study, I employed a Monte Carlo simulation (MCS) to assess the uncertainty of the model results. The results show that the level of uncertainty varied for different indicators (see Figure 4-8).

Figure 4-8.a shows the results from MCS of DMC indicators. As illustrated in the figure, from MCS the uncertainty of DMC ranges between ±12% and ±22% throughout the period; it is lower at the beginning of the studied period and highest in the year 2005. Regarding the characteristics of Lao PDR, as it is ongoing in its transition from a biomass based economy to an industrial based economy, the massive amount of materials for infrastructure development is highly dependent on domestic materials as well as some imports of machinery and other construction materials. DE clearly played an important role in the uncertainty of DMC in 2005 when the amount of construction materials required, on which the amount used in the accounting was estimated, rapidly accelerated due to many construction activities in the country. Another aggregated indicator on the input side is DMI. Due to the small amount of imports, DMI almost mirrors DMC (see Figure 4-8.c).

Taking the uncertainty level of DE and IMP, and EXP into consideration showed that the uncertainty of the results was mainly influenced by uncertainty in DE. This is the general phenomenon seen in national MFA when trading is less than DE. The Patrício et al. (2015) study also mentioned that the uncertainty of DMC is highly dependent on the relationship between trade and materials consumption. The uncertainty of DMI and DMC in 2015 was ±14% (Figure 4-8.b and Figure 4-8.d). The recent MFA study at the country level that perform uncertainty analysis was limited. Thus, the comparison was done by comparing the results of this study to an available study at regional level, which had uncertainty ranges from 1.9% to 5.3% for DMI, and 4.2% to 22.6% for DMC (Patrício et al. 2015).

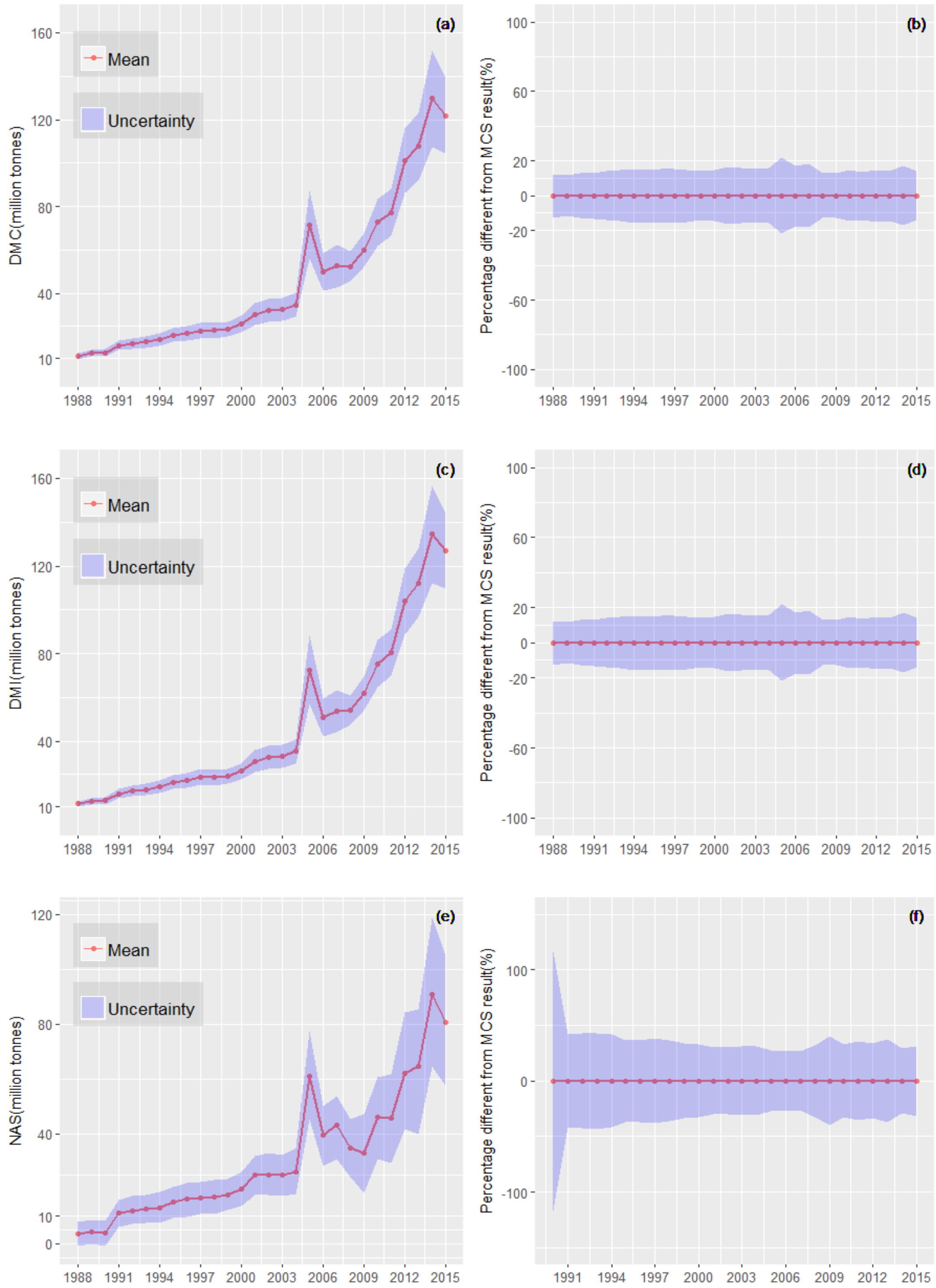


Figure 4-8 Comparison of MCS with sensitivity analysis and Percentage different from MCS: (a) and (b) are DMC results; (d) and (e) are DMI results; (e) and (f) are NAS results, respectively.

Figure 4-8.e shows results for NAS from the MCS. At this stage, NAS was calculated by balancing inputs and outputs indicators of the national economy systems boundary. Patrício et al. (2015) mentioned that most MFA studies calculated using the material balancing approach simply did not take this into account. Following the common balancing approach, many levels of uncertainty were aggregated into NAS, and the calculations resulted in high uncertainty. The highest uncertainty range is more than ±100% in the 1990s, decreasing to under ±50%, and around ±30% in 2015 (see Figure 4-8.f). The high level of uncertainty indicated how much poor data quality and high uncertainty affect uncertainty levels of NAS. The reason behind such abnormal uncertainty levels in the late 1990s is that when low quality data such as DPO and balancing items dominate other flows in the system such as DE, IMP, and EXP, the high uncertainty of those indicators will likely to take the lead in the uncertainty of NAS. On the other hand, when higher quality data indicators dominate other flows, high uncertainty in estimated data has less influence on the results, as seen in the decreasing uncertainty level of NAS in Figure 4-8.f.

Due to the characteristic of material flow balancing, the results for NAS from the MCS contains the highest uncertainty among the indicators, I suggest that using estimated data for DPO and balancing items to calculate NAS from the material balancing approach should be considered the least preferred option.

All the MCS results shows that when DE becomes a more important indicator in terms of supplying resource national economic development, strong characteristics of DE such as the availability of official statistics, and better estimation approaches, will allow practitioners and policymakers to focus on resource targets to accelerate and improve the quality of MFA studies. This will provide valuable information to use in policy decisions as well as planning tools. However, considering the high uncertainty of NAS from materials balancing, further investigation should seek other approaches for NAS accounting.

4.9 Comparison results from this study with UNEP International Resource Panel's database

In this dissertation, material flows accounting of Lao PDR has been conducted based on national statistics and local knowledge for the parameters used to estimate missing data in the statistics for the first time. It adds considerable value to the evidence-base information of Lao PDR's resource use which, until now, had to rely on international data. UNEP's database (UNEP 2017a; UNEP IRP 2018b) is the most comprehensive global materials flow accounting covers more than 200 countries globally. However, this database constructed based on international datasets from various international organizations. To show how the national statistics and local knowledge could contribute to provide more realistic EW-MFA results at national level, author compares the results from this dissertation and the data from UNEP's database (UNEP 2017a).

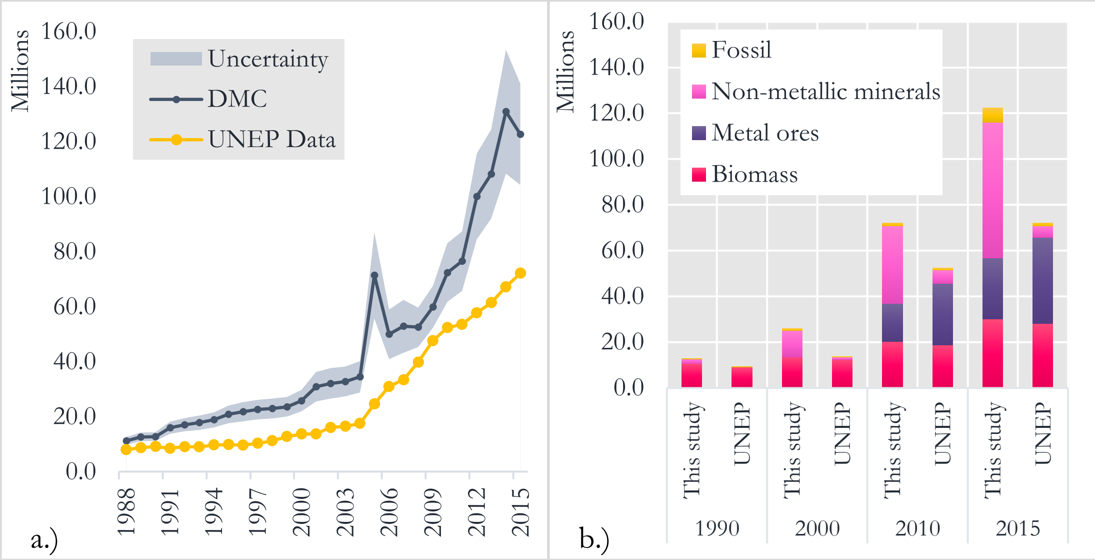


Figure 4-9. Comparison of results of this study and results from UNEP (2017), a) total DE, including uncertainty for this study, b) DE by main categories

When compare the results for DE from this study to the accounts provided by UNEP, the significant differences are observed, especially for metal ores and non-metallic minerals but to a lesser extent also for biomass (see Figure 4-9.b). The significant differences between this study and UNEP's database are due to different assumptions made for the estimation of non-metallic minerals and the data used to account for metal ores. In this study, it is the first time that sand and gravel for construction have been estimated based on cement consumption and the newly developed material intensity of concrete in Lao PDR. I also included an estimation of aggregates used for road construction based on the additional length of road network in the country and the average material intensity for road construction. For metals, I directly used the total amount of ores processed rather than an estimation of gross ores using ore grades and metal products.

To better understand the relationship between human development and resource consumption, UNEP (2016) used the national level human development index (HDI) as the metric to cluster levels of resource extraction, consumption and trade by four major groups of countries: Low HDI, Medium HDI, High HDI, and Very High HDI. The development of HDI in Laos grew slowly, about 1.5 times compared to HDI in 1990. In 2015 Laos was considered a medium HDI country by the index provided by UNDP (2016).

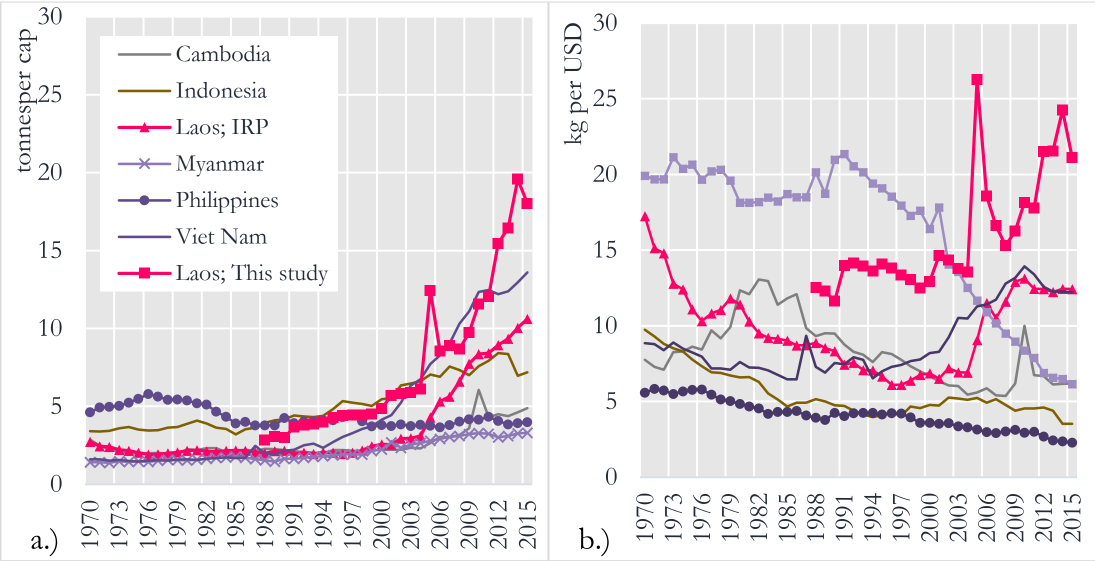


Figure 4-10. a. Metabolic rate (DMC per capita), b. Resource intensity (DMC per GDP) in Medium HDI countries of ASEAN

Figure 4-10 shows the comparison of metabolic rate and materials intensity of a group of medium HDI countries in Southeast Asia which are all members of the Association of Southeast Asian Nations (ASEAN). Data for Lao PDR from this study is compared to data for ASEAN countries from the UNEP IRP (2018b) dataset. Lao PDR shows the highest per-capita DMC of all six ASEAN members and has by far the worst resource efficiency, almost double that of other ASEAN medium HDI countries. Of course, there are strong possibility that the accountings for other countries using UNEP's dataset have similar issues with Lao's accounting and their DMC values are bigger. However, even when comparing MI and metabolic rate of Lao PDR using UNEP IRP (2018b) dataset, the values for Lao PDR are still higher but closer to other countries, indicating that the various data sources used in the MFA accounting influenced the comparison. The Lao economy uses domestic natural resource in a less efficient way than its neighbors, is less successful in building local value-adding industries, and accepts the highest environmental pressure on its domestic territory of the six ASEAN economies I are comparing. It is questionable whether this pathway of material extraction for infrastructure supporting primary resource exports, which has not translated into human wellbeing sufficiently well, is a good economic strategy for Lao PDR's long-term economic prospects.

4.10 EW-MFA indicators vs. Raw Material Equivalents indicators

EW-MFA framework directly measures material that actually extracted and trades within the defined system boundary. Trade flows are accounted as the net weight of products when they cross the national border, without considering the total raw materials used behind the production processes of such products. This direct accounting may overlook the environmental pressure related to the products imported and exported.

Eurostat developed framework that could capture the total raw materials required to produce the traded products called Raw Material Equivalents (RME). In order to convert import and export from actual weight into RME unit, the Input-Output table and life-cycle-inventory data are used. Eurostat presents three approaches for estimation of RME, namely coefficient approach, Input-Output table approach, and hybrid approach.

In this dissertation, due to the lack of IOT for this case study, coefficient approach is implemented. Eurostat RME provides EU-level RME coefficient matrices of 52 materials categories and 166 products for imports and exports. To implemented the RME approach for Lao PDR, the coefficients for converting import and exports are based on Eurostat RME framework. Accounting materials flows in RME could provide DMI and DMC in RME based unit by following the traditional EW-MFA accounting rule. Raw Material Input (RMI) corresponds with DMI and Raw Material Consumption (RMC) corresponds to DMC.

Figure 4-11 shows comparison of imports of Lao PDR in year 2015 in actual import weight and IMP in RME. Total import when accounted in RME is 12.4 million tonnes, higher than actual import by factor of 1.6. Biomass products and non-metallic minerals products show slightly higher values when accounted as RME based. Metal products and fossil fuels show significantly different. The metal imported products increased from 1.1

million tonnes to 1.7 million tonnes, while fossil fuels products become higher more than 3 times in RME. Details at subcategories products are shown in Figure 4-11.b.

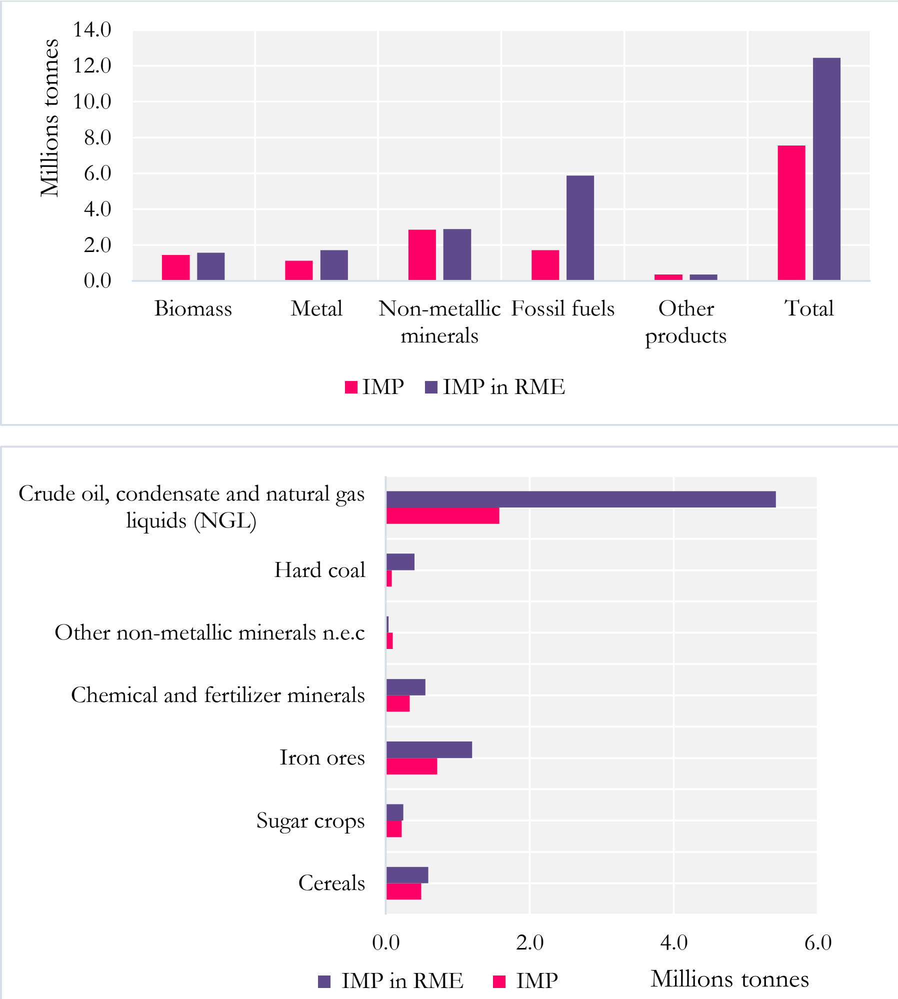
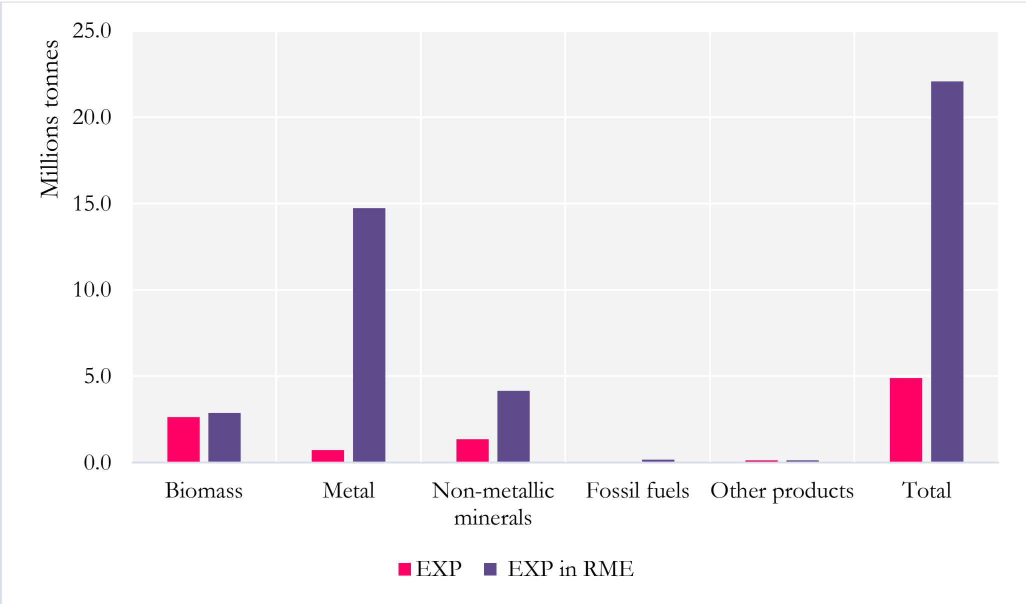


Figure 4-11 Imports of Lao PDR in 2015 in EW-MFA (IMP) and RME based units (IMP in RME), a) in four main categories b) in selected important products

For the case of export, differences become even more. EXP in RME surpassed almost 5 times. Due to the primary materials extractive sectors in Lao PDR which the metal content and concentrate are mainly exported, the export in RME higher than the export about 20 times (see Figure 4-12). Non-metallic minerals, which also involve quite high volume of raw materials required to produce, show higher value by factor of 3.1 compared to actual export. There is no significant difference in export of biomass.



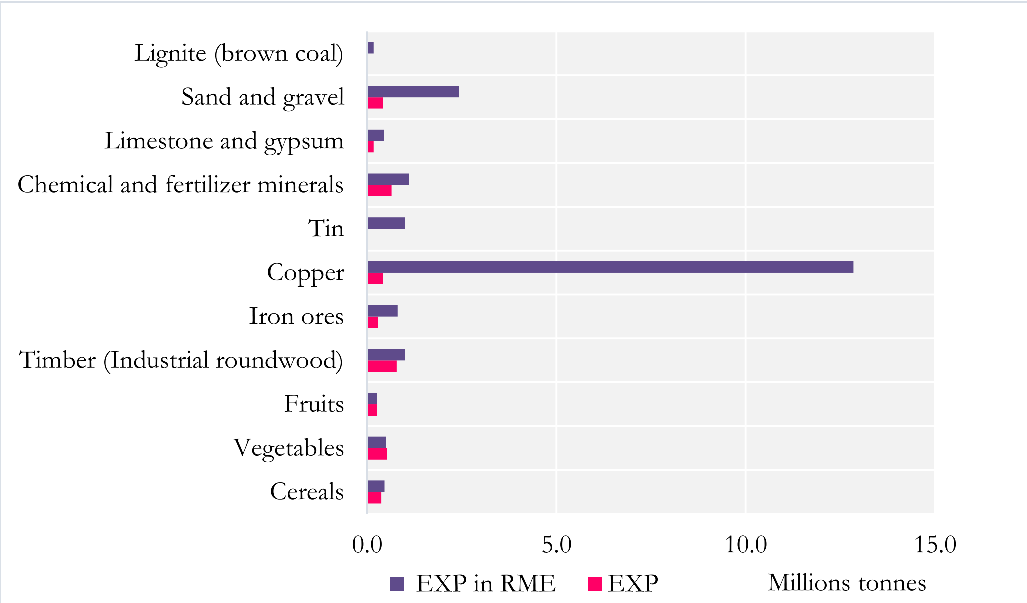


Figure 4-12 Export of Lao PDR in 2015 in EW-MFA (IMP) and RME based units (EXP in RME) a) in four main categories b) in selected important products

In EW-MFA, physical trade balance is the indicators to measure the dependency of the country on global resource market. Figure 4-13 show that in 2015 PTB is surpass as 2.6 million tonnes indicating that country is net importer, which imply the country rely on materials from other countries. Based on PTB, Lao PDR relies on metal, non-mineral, and fossil fuels from other country, and provides biomass products to the global resource market. However, Raw Material Trade Balance (RTB) shows that Lao PDR is net exporter of biomass, metal, and non-metallic minerals products. The total gross ores required to produce metal content and metal concentrate products contribute to the majority of RTB.

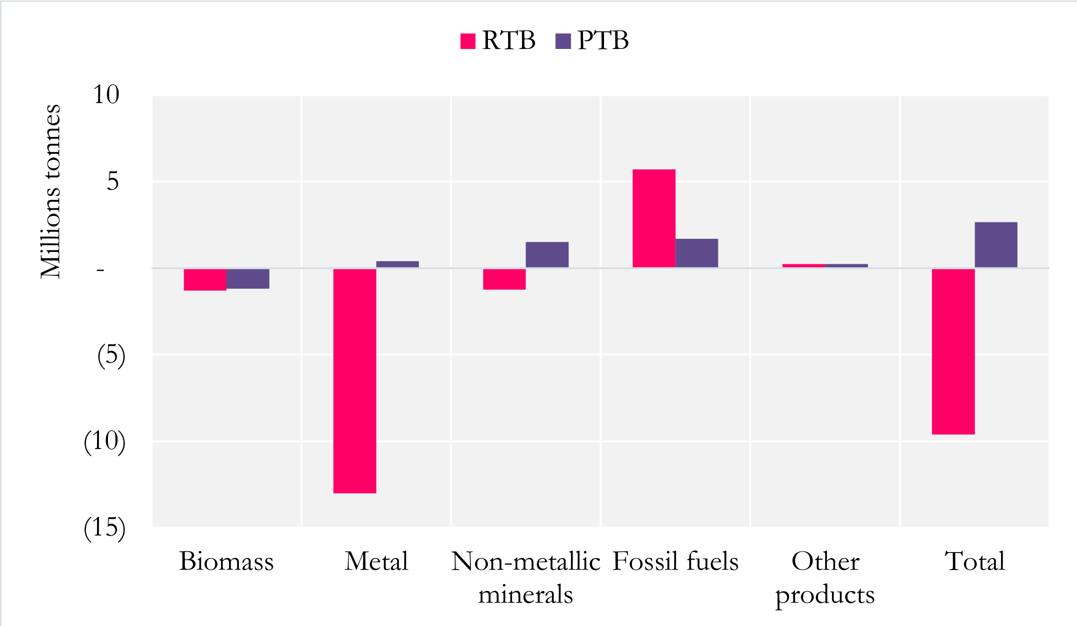


Figure 4-13 Physical trade balance (PTB) and Raw Material Trade Balance (RTB) of Lao PDR in 2015

Other two indicators that could be obtained in RME based on EW-MFA's accounting rules are Raw Material Consumption (RMC) which is corresponds to DMC and Raw Material Input (RMI) which corresponds to DMI. As mentioned, due to the low volume of the trades in Lao PDR, DMI and DMC are almost identical. In 2015, DMC is lower than DMI by only 4%. But this is not the case when material flow accounted in REM. RMC is lower than RMI by 17%, which imply that the RMI is contributed to produce the products for exports, which in this case is metal content and concentrate products. RMC of metal and non-metallic minerals are increased indicating that these materials are mainly used to produce the products for exports.

Comparing resource productivity in direct material and in RME of Laos for year 2015 shows that RP in RME is lower by 12% (see Figure 4-14). This comparison reveals that if the resource efficiency measure based on direct material flow, the resource efficiency of country that relies on imported primary resource would be lower because the imported amount accounted in direct material flow dose not captured the raw materials required to produce such products. On the one hand, the country that relies on exporting of primary resource seems to take such deficit.

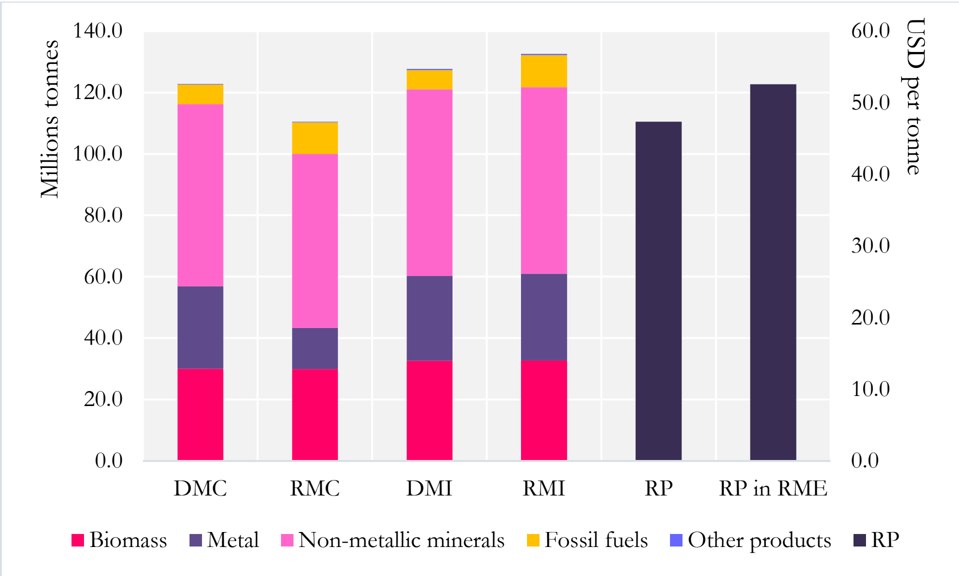


Figure 4-14 EW-MFA indicators Direct vs. Raw Material Equivalents of Lao PDR for year 2015

CHAPTER 5
Implementation of improved EW-MFA for other developing countries: Case study of Bangladesh

5.1 Introduction

Bangladesh, a sovereign developing nation in South Asia appeared on the world map as an independent country during 1971. Geographically it lies between 20°34' - 26°38' N latitude and 88°01' - 92°41' E longitude. It is bounded by India on its three sides (the west, north and northeast) whereas by Myanmar on one side (southeast). The southern part of the country is bounded by the Bay of Bengal. The total area of the country is 1, 47,570 sq. km (Bangladesh Bureau of Statistics 2018).

The physiography of Bangladesh is diverse. It has the hilly landscapes in the northeastern and southeastern part. A major portion of the country's landscape is the floodplain land that is highly fertile due to the composition of silt. It enjoys a sub-tropical climate with six distinct season in a year i.e. winter, summer, rainy, autumn, late autumn and spring. The average temperature of the country ranges between 7°C-37°C (Bangladesh Bureau of Statistics 2017).

The present population of Bangladesh is approximately 150 million with a growth rate of 1.37% per annum according to the latest census report (Bangladesh Bureau of Statistics 2011). The population density of the country is 976 per sq. km (BBS, 2011).

Bangladesh is an agriculture-based country. It is the largest sector that contributes to economy of the country with an estimated 11% share to the total GDP while accommodating more than 40% of the total labor force. Rice, jute, vegetables, sugarcane, pulse, tea, tobacco are the principal crops of the country. It is also rich in fishery resource due to its innumerable rivers, wetlands, canals, ponds etc. (Bangladesh Bureau of Statistics 2017).

Despite the fact that Bangladesh is rich in agricultural resource when it comes about minerals, the country is poor. It has a few proven mineral resource although the deposit of natural gas is enormous. Bangladesh has coal it its soil however, due to technological barrier, it can only produce the coal from a few fields.

At present, the country is actually transitioning from agriculture to an industrialized based economy. A major number of large-scale industries are working on the country. The most prominent industry among the others is the ready-made garments, an export oriented one. The other industries of the country are: pharmaceuticals, fertilizer, iron and steel, cement and so on.

Utilizing the local knowledge and national statistics could improve the EW-MFA results, especially for developing countries, which show in recent case studies of developing countries in the South East Asia region (Vilaysouk et al. 2017, 2018; Martinico-Perez et al. 2018b; Martinico-Perez et al. 2018a). Bangladesh is selected as addition case study, to test transferability of the improved EW-MFA framework of this dissertation, for several reasons. First, as the country is in the transitioning stage of resource use from biomass–based to non-metallic minerals and metal–based economy. Second, due to the characteristics of the country that lack of domestic metal mineral resource. Last but not least, as a case study of developing country but with high population density. Based on these reasons, the implementation of the improved EW-MFA would provide additional knowledge of resource use for this developing country in difference outlook.

5.2 Methodology and Data sources

The methodology introduced in Chapter 3 is once again applied to the case study. Due to the limitation of data availability, only main EW-MFA accounts are conducted. This case study includes the Domestic Extraction account (DE), Trades account (Imports and Exports), and derived indicators from EW-MFA framework such as Domestic Material Consumption (DMC), and Physical Trades Balance (PTB). Resource efficiency indicators, namely Resource Productivity and Resource Intensity, are included. The results from this study are compared to the IRP's database (UNEP IRP 2018b) for metabolic rate (DMC/capita) and other important EW-MFA indicators. Due to the availability of the data, author choices two time steps for year 2010 and 2015 to provide the snapshots of resource uses pattern in developing Bangladesh.

Statistical data used to compile EW-MFA is mainly rely on national statistics. Statistical Yearbook of Bangladesh (Bangladesh Bureau of Statistics 2015, 2010) is the main source of statistical data used in this study. Due to the underreported values for brick production in the yearbook, the data from technical reports (World Bank 2011; Department of Environment 2017) of brick production was used to substitute the values reported in yearbook. When some data is missing in the national statistics, which is the general case for developing countries, the international data sources are used to fill the data gaps. The FAO database is used to fill the data gaps for fuel wood and timber. For the trade data, COMTRADE is the main sources for compiling. The data in COMTRADE for Bangladesh is cover from year 1988 to 2015. For the snapshot year 2010 and 2015, the imports data cover physical and monetary units for more than 94% of total records and the exports is more than 97%. Thus, in this case COMTRADE database could be considered as a good data source for compiling trade account. For other missing data which could not be obtained from any data sources, the estimation procedures in Chapter 3 is applied.

5.3 Results and Discussion

5.3.1 Domestic Extraction (DE) and Domestic Material Consumption (DMC)

Figure 5-1 shows the DE and DMC of Bangladesh. The DE in 2010 is 789.5 million tonnes. Majority of DE is non-metallic minerals, accounted for 559.1 million tonnes (70% of total DE), which is dominated by the clays used for brick production. Biomass accounted for 213 million tonnes, which equal to 27% of total DE. The remaining of DE is fossil fuels and energy carrier materials. In Bangladesh, there is no extraction of metal ores. Thus the DE for this material category is not showing in the figure. In 2015, DE increased to 931.7 million tonnes with annual growth rate of 3.4%. The Biomass growth with the slowest rate as only 1.6% per year, followed by non-metallic minerals as 3.9% and the fastest growth materials is fossil fuels as 6.6% per year. The sharing of each material remained the same as previous observed year.

DMC indicates the material consumption in the defined system considering DE, Imports and Exports. In 2010, due to low amount of trades (import and export), the DMC figure almost mirror the DE. This situation is also observed in other developing newly countries (Vilaysouk et al. 2017, 2018; Martinico-Perez et al. 2018b; Martinico-Perez et al. 2018a). The DMC in 2010 was 818.8 million tonnes, approximately 3.7% higher than DE. DMC included additional materials from trades consisting of metals as 2.2 million tonnes and other products as 1.7 million tonnes. The non-metallic minerals remained as the most dominant materials in total DMC which accounted for more than 70%. This pattern of material consumption is really unique among other newly developing countries. DMC increased to 980.8 million tonnes in 2015 with annual growth rate of 3.7%. From 2010 to 2015, the main driver of the DMC is non-metallic minerals.

Applying the improved EW-MFA framework, specifically developed for developing countries, and the national statistical data, the significant differences between the IRP's database and the results from this study could be observed. The IRP's MFA global database is constructed based on various international dataset to keep the consistency in the compiling process, which overlook the local condition for small developing countries. Also, in the international database, some data is estimated based which sometimes under-reported or over-reported. In the case of Bangladesh, for the biomass and metal, the derived indicators of DE and DMC are quite consistent between this study and IRP's data. A huge gap exists in the non-metallic minerals, which is always important material for infrastructure development in developing economies, including Bangladesh. In the IRP's database, the non-metallic minerals category is mainly estimated based on the apparent consumption of cement, bitumen, and brick. The main contributor for this big difference is the clays required to produce the bricks. In Bangladesh, brick is very important material for building construction (Ministry of Environment and Forests of Bangladesh 2017). However, the statistics for brick production is poorly recorded even in the national statistics yearbook. The data used to compile the clays required for brick production is based on the technical report on sustainable brick production in Bangladesh (Ministry of Environment and Forests of Bangladesh 2017). Considering bricks are important materials in some developing nations' infrastructures, this underestimation in IRP database may also exist for other nations.

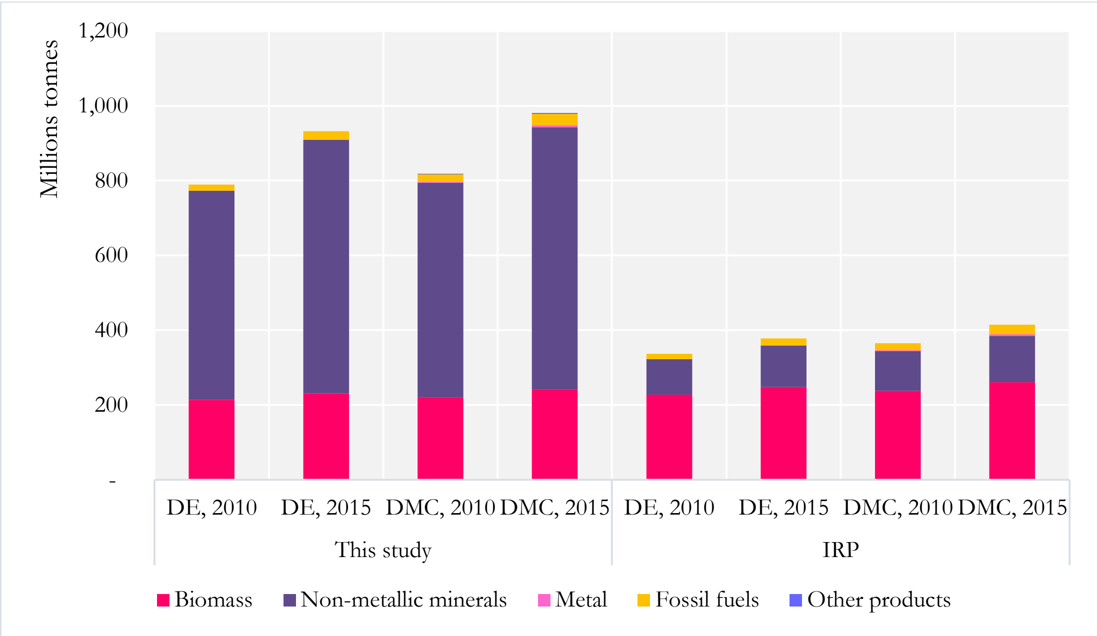


Figure 5-1 Domestic Extraction and Domestic Material Consumption of Bangladesh

5.3.2 Imports and Exports

Trades account is one the most difficult accounting in EW-MFA for many developing countries due to the lack of reliable statistical data. In this dissertation, the trades account is compiled based on the UN COMTRADE database. The trades data of Bangladesh in the database cover more than 94% of total records for import and more than 97% for the exports.

Total imports, including raw materials and processed products, in 2010 was 35.8 million tonnes (see Figure 5-2). Non-metallic mineral was the biggest category of import with shares of 45%, followed by biomass as 33%, 10% of fossil fuels, and 6% each for metal and other products categories. In 2015, imports raise to 57.1 million tones and the shares of each material remained almost the same. The imports of important materials for development and maintenance infrastructure, capital stocks, and provide services to improve well-being, with could not provide by domestic extraction, such metal and fossil fuels grown with faster rate as 21.8% and 15.3% per year, respectively. Imports of biomass grow at slower rate of 6.6% per year. The main products of imported biomass are crops products with total amount of 16.5 million tonnes in 2015. Imports of non-metallic minerals products are mainly the cement of other construction materials. For the metal mainly is the iron and steel. Bangladesh has also depended on the imports of petroleum oil and coal from other countries with total amount of 7.1 million tonnes in 2015 for their domestic energy consumption.

The main export of Bangladesh is biomass category which is mainly cloths and textile bast fibers products. Total amount of this category was 4.8 million tonnes in 2010 and increased to 6.4 million tonnes in 2015. The remaining 1.7 million tonnes and 1.5 million tonnes were the exports of non-metallic minerals, metal, fossil fuels, and other products in 2010 and 2015.

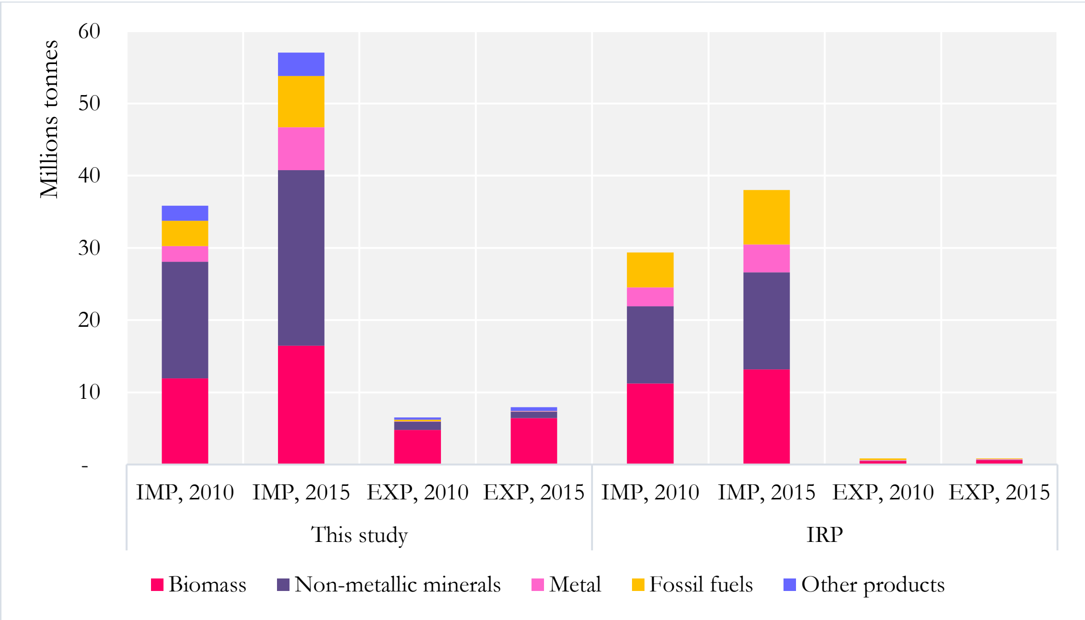


Figure 5-2 Trades of materials and products of Bangladesh

Comparing the imports and exports between this study and IRP's database, the differences are also found. The imports amount in IRP seems to be lower than results from this study. Although both studies used international datasets but the difference data sources and methodologies are used for compilation. IRP's database constructed trades account for individual main material categories (biomass, metal, non-metallic minerals, and fossil fuels) based on different data sources. In this dissertation, the COMTRADE database was used for compiling and the conversion from HS-Code to MFA code is based on Eurostat conversion code. The percentage difference between this study and IRP's database of imports is 19.9% for year 2010 and about 40% in 2015. The differences are even bigger for exports as could be observed as 153.5% and 161.2% for year 2010 and 2015. As mentioned earlier the main exports products of Bangladesh is cloths and accessory, and textile bast fibers. These products are not recorded in FAO database which used to compile the trade of biomass in IRP's database.

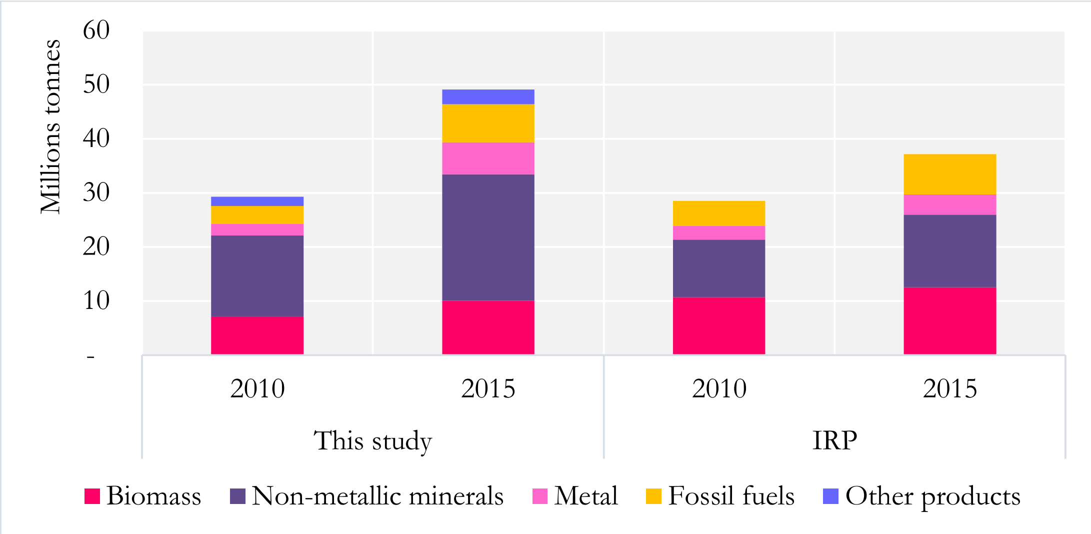


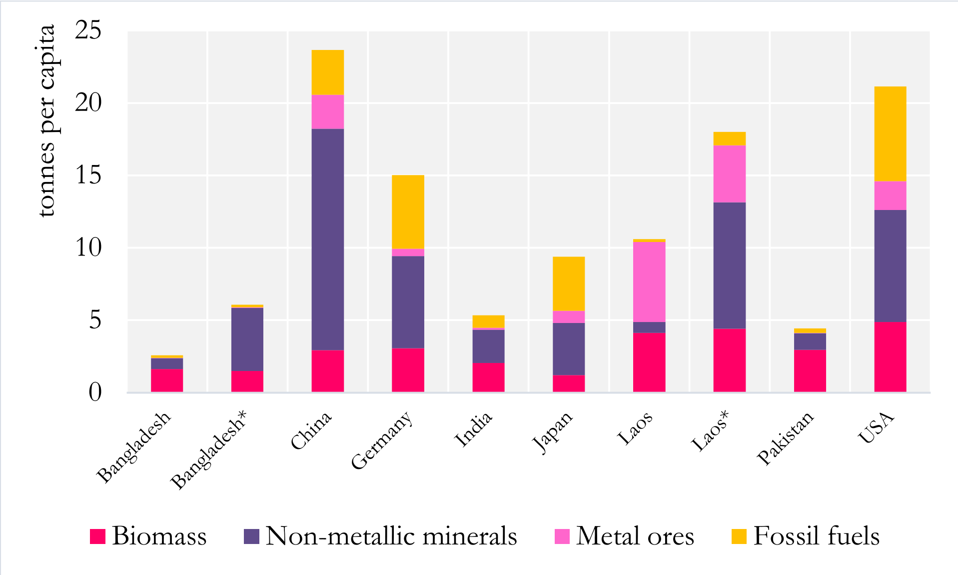
Figure 5-3 Physical Trade Balance of Bangladesh

Figure 5-3 shows the physical trade balance of Bangladesh in year 2010 and 2015. The results show that Bangladesh is net importer of all materials categories. The increasing trends is similar to the trends of imports. In terms of dependency of global resource, more than half of resource dependency is non-metallic minerals. The comparison of this result and IRP shows closer gap. The percentage difference between the studies is 2.8% for year 2010 and increase to 27.7% in 2015. The significant difference of exports does not influence the PTB due to its small amount compared to imports. The differences of imports of non-metallic minerals and metal are the main contributors.

5.3.3 Metabolic rate and Resource Productivity

Metabolic rate is term used to descript the DMC per capita in EW-MFA framework. Figure 5-4 shows the metabolic rate of selected countries to show the comparison between very high Human Development Index (HDI) countries (Germany, Japan and United States) and medium HDI counties (Bangladesh, China, India, Laos, and Pakistan). The improved results from this study show that metabolic rate of Bangladesh in 2015 was 6.1 tonnes/cap which is quite common for developing countries except low metabolic rate of metal ores and fossils fuels. The metabolic rate of Bangladesh from IRP's database was lower than this study which was only 2.6 tonnes/cap. The big difference between this study and IRP's database is metabolic rate of non-metallic minerals which is difference more than 5 times. However, comparing to other developing countries with same level of HDI, metabolic rate of non-metallic minerals of Bangladesh is comparable.

The resource productivity of Bangladesh indicates the resource efficiency improvement. The results from this study is consistence with the IRP's results regarding the improving trends of resource productivity. However, in terms of value, the resource productivity from this study is relatively lower than the IRP's result. The result from this dissertation shows that the resource productivity increased from 0.09 USD per kg to 0.11 USD per kg, which is lower than the result reported in the IRP's database as 0.21 USD per kg and 0.25 USD per kg. The difference of the DMC result caused huge difference in resource productivity values. The resource productivity could be improved by advancing the technology used in the industry sector that required less resource, or by increasing the value-addition of the economic sectors. Based on the available information analyzed in this study, the concrete conclusion for such resource productivity improvement in Bangladesh is out of the scope of this study. The longer time series of EW-MFA and deeper analysis are required to answer such questions.



*Note: *indicate the results from this dissertation, for other is the data from IRP*

Figure 5-4 Metabolic rate in 2015 of selected countries

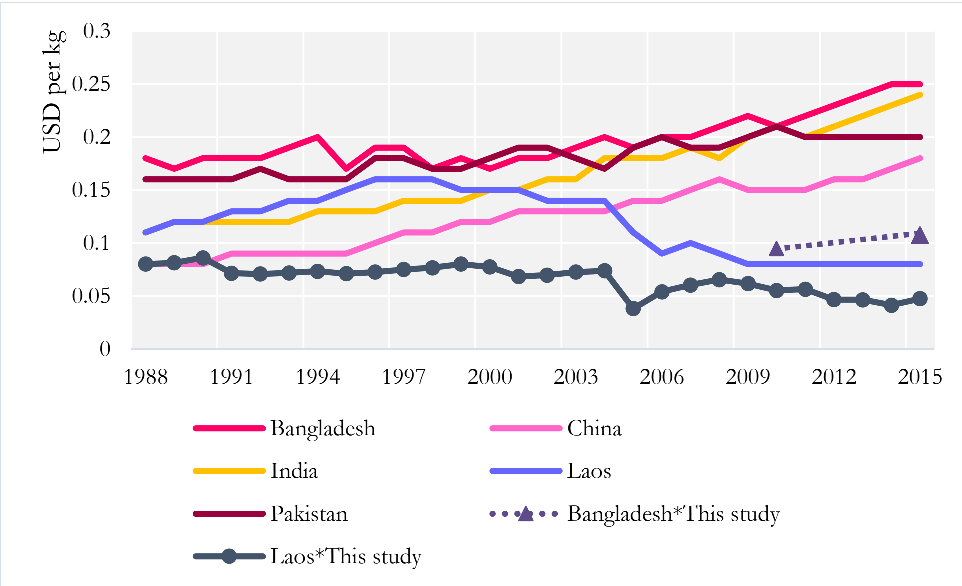


Figure 5-5 Resource Productivity of Bangladesh and Selected Countries

5.4 Conclusion

Based on the improved EW-MFA for developing countries from this dissertation and national statistical data, the EW-MFA could be improved. The improvement occurred in all accounts considered in this study. The results for DE of biomass show the consistence and high quality of the agriculture statistics in Bangladesh. The big improvements go for the trade accounting and DE of non-metallic minerals. The new results were compared to previous study of IRP and the potential reasons of such differences are identified.

The new results show that within two time steps 2010 and 2015 all studied indicators are on the rising trends. This is the common in developing countries. The DMC increased from 818.8 million tonnes in 2010 to 980.8 million tonnes in 2015 with annual growth rate of 3.3% resulting in total metabolic rate of 6.1 tonnes/capita. The metabolic rate of Bangladesh is within the comparable range with other developing countries having similar level of HDI. The analysis shows that within the studied period, there is moderate improvement of resource productivity but the reasons behind such improvement could not be drawn based on the analyzed information in this study. The results from this study have proved the concept of utilizing local knowledge and national statistics for compiling EW-MFA could provide realistic results compared to the one mainly relied on international datasets.

CHAPTER 6
Resource Efficiency Indicators as Evidence-base information for Sustainable Resource Management Policies: a case study for Lao PDR

6.1 Introduction

UNEP summarized five main reasons why resource efficiency can be core-concept for sustainable development. These includes scarcity of resource, volatility of commodities price, high resource prices, environmental impacts related to resource extraction and use, and innovation from improvement of resource efficiency (UNEP 2017b).

Since the first seminal EW-MFA comparative studies in 1990s, EW-MFA has provided the information, indicators for sustainable resource management policies across the globe. EW-MFA framework has reached maturity in the past couple of decades (Fischer-Kowalski et al. 2011) and has been officially accounted in many countries, most notably in the European Union (EU) and Japan. In these countries, EW-MFA has become a core component of environmental accounting and serves as a basis for evidence-base policy making. The Japanese government's Sound Material Cycle Society high-level policy objective, for instance, uses three indicators derived from material flow accounts namely resource productivity, cyclical rate, and final disposal to support the implementation of a 3Rs policy agenda (Takiguchi and Takemoto 2008). Similarly, in the EU, resource productivity is used as the lead indicator, along with other EW-MFA indicators, in the EU Resource Efficiency Scoreboard to measure progress toward increased resource efficiency of individual Member States and the European Union as a whole (European Commission 2017).

Resource efficiency has become an important objective of the G7 major economies, which launched a new initiative in Germany in 2016 that requires the integration of resource management and economic policy in one coherent framework (Bringezu et al. 2016). In the G7 Toyama Environment Ministers' Meeting held at Toyama, Japan in May 2016, the Toyama Framework on Material Cycles reaffirmed the G7's active leadership in environmental policies with the common vision of enhancing resource efficiency and promoting the 3Rs (Ministry of the Environment Government of Japan 2016). Implementation of the new Sustainable Development Goals (SDGs) and the monitoring of progress toward goals and targets that address resource productivity, sustainable resource management and resource efficiency at industry level are especially important for low-income countries that have large development needs and require timely and affordable natural resource. Despite this essential need for the materials that will underpin human development and prosperity, many low-income countries use their domestic natural resource to generate export revenues, i.e. their resource benefit people in other parts of the world, mostly in high income countries (Wiedmann et al. 2015).

6.2 Resource Efficiency in Lao PDR

In this dissertation, the resource efficiency of Lao PDR is evaluated using three main indicators suggested by IRP, resource intensity, emission intensity and resource productivity. Figure 6-1.a shows the evolution of the resource intensity of the Lao economy between 1988 and 2015. While most economies improve their resource intensity as they modernize, this has not been the case for Lao PDR. The resource intensity of the economy almost doubled during the past three decades. It increased from an already very high level of 12.5 kg per USD in 1988 to 21.1 kg per USD in 2015 (see Figure 6-1.a). This indicates that material use in Lao PDR has become less economically efficient throughout the whole period with a few years of insignificant efficiency improvements in between. Resource intensity peaked in 2005 when a number of large hydropower construction projects started, most notably Nam Theun 2 hydropower plant, which required an enormous amount of construction materials. Overall, material use in the Lao economy has grown much faster than economic activity, i.e. GDP and increases in material extraction and use have not been benefiting the economy in terms of economic growth and increased human wellbeing.

Another important feature of the material flow analysis is the metabolic rate, which is expressed as domestic material consumption (DMC) per capita. Figure 6-1.b shows per-capita DMC by main material categories, and a category for other products. Because trade flows are still very small, DMC is only slightly different from DE. From 1988 to 2004 per-capita DMC doubled from 2.8 to around 6 tonnes but then increased sharply to 9.8 tonnes per capita in 2009 and around 20 tonnes per capita in 2015. Overall natural resource use in Lao PDR has been transformed from a biomass-based to a metal ore and non-metallic minerals -based economy, indicated by the fast increasing DMC per capita of these materials. In 1988, the metabolic rate of non-metallic minerals in Lao PDR was at 0.5 tonnes per capita and it had increased to 8.7 tonnes per capita by 2015. Metal ores and fossil fuels also grew rapidly and increased from less than 0.1 tonnes per capita in 1988 to 4.8 tonnes per capita in 2015. Most of this growth has been related to export industries and has not resulted in large improvements in domestic infrastructure.

Per-capita DMC of biomass has grown more slowly, increasing from 2.5 tonnes per capita in 1988 to 4.4 tonnes per capita in 2015. The increase in DMC of non-metallic minerals will be of benefit to the Lao economy and its people as these materials are mainly used to construct buildings, roads, hydropower plants, and other infrastructure which underpin the continuous urbanization and industrialization of the country. Metal ores are a different case with a large fraction of DMC ending up as mining waste and tailings at mining sites, causing a variety of environmental issues including toxic waste and pollution and requiring long-term management.

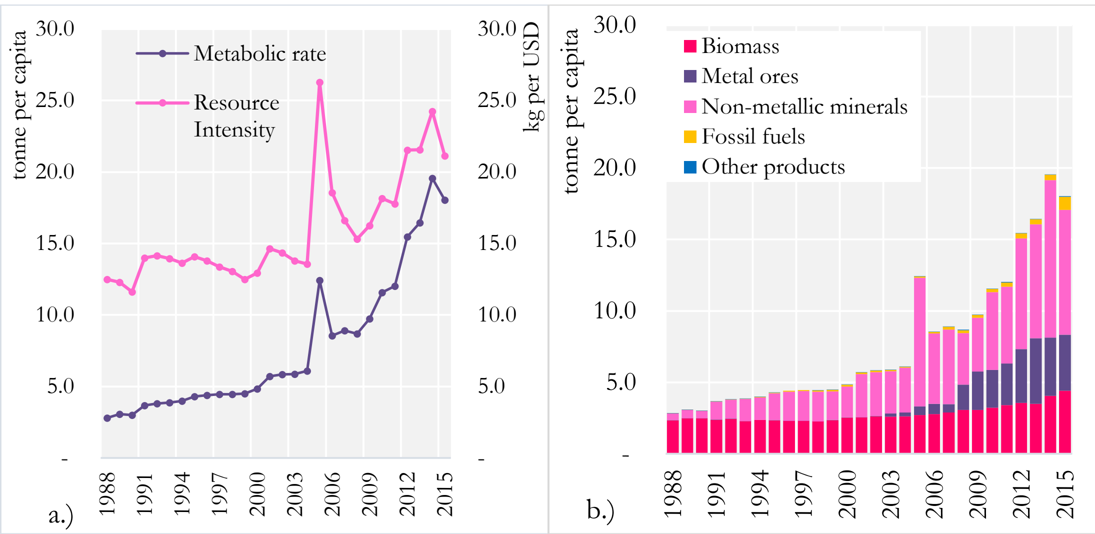


Figure 6-1. a. Resource intensity (DMC per GDP) and metabolic rate (DMC per capita), b. Metabolic rate by main materials categories of Lao PDR in 1988–2015

As Lao PDR establishes its infrastructure and industrial capital and delivers a higher material standard of living to its people, material use will grow, as has been the case in many other Asian developing economies (UNDP 2016). The emissions intensity of the national economy is expressed as DPO per unit of GDP. From 1988 to 2000, there was a gradual improvement in the waste intensity of the Lao economy, with GDP growing faster than the associated waste flows (see Figure 6-2). Soon after the large-scale mining industries started operation, however, there was a remarkable increase in waste intensity. From 2000 until now, waste and emissions intensity rose from a level of 2.8 kg per USD to 8.5 kg per USD in 2013, slightly decreasing thereafter to 7.1 kg per USD in 2015 which caused by decreasing of mining production.

From the results of EW-MFA linked to economic activity by GDP, three important resource efficiency indicators, which includes resource productivity, resource intensity, and emission intensity, could be derived. The summary of the trends of these indicators from 1988 to 2015 are summarized in the Figure 6-2.

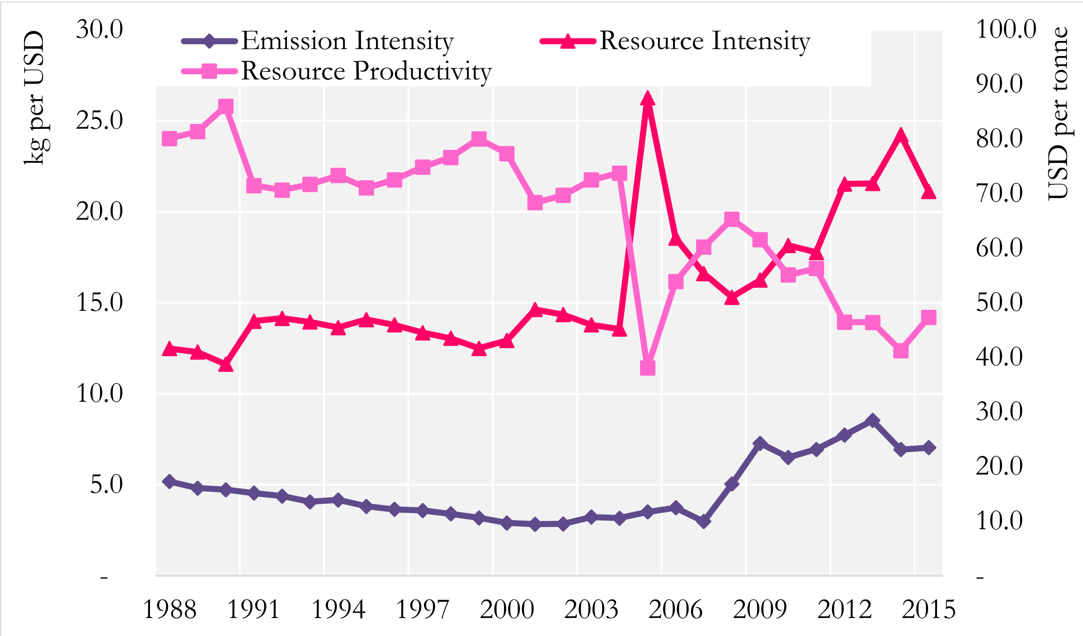


Figure 6-2 Resource Efficiency Indicators of Lao PDR; Resource Intensity and Emission Intensity refer to the left axis, resource productivity refers to right axis.

6.3 Trends and Drivers of Resource Consumption: IPAT Analysis

Figure 6-3.a shows the long-term trends in a set of indicators including DMC, GDP and MI as well as population growth and HDI improvements. Overall, material use has grown much faster compared to economic development and improvements in technology and resource intensity. Over the past three decades, DMC increased almost 12-fold, GDP about 6-fold, and as a result MI doubled. The very rapid growth in DMC, outpacing GDP, indicates the development path of the Lao economy has relied on bulk materials for infrastructure development and on export-oriented primary resource sectors for now. As a consequence, there has not been decoupling of material use and environmental burden from affluence over the past three decades. Population and increases in human development both showed more benign growth trajectories compared to growth in resource use and the economy.

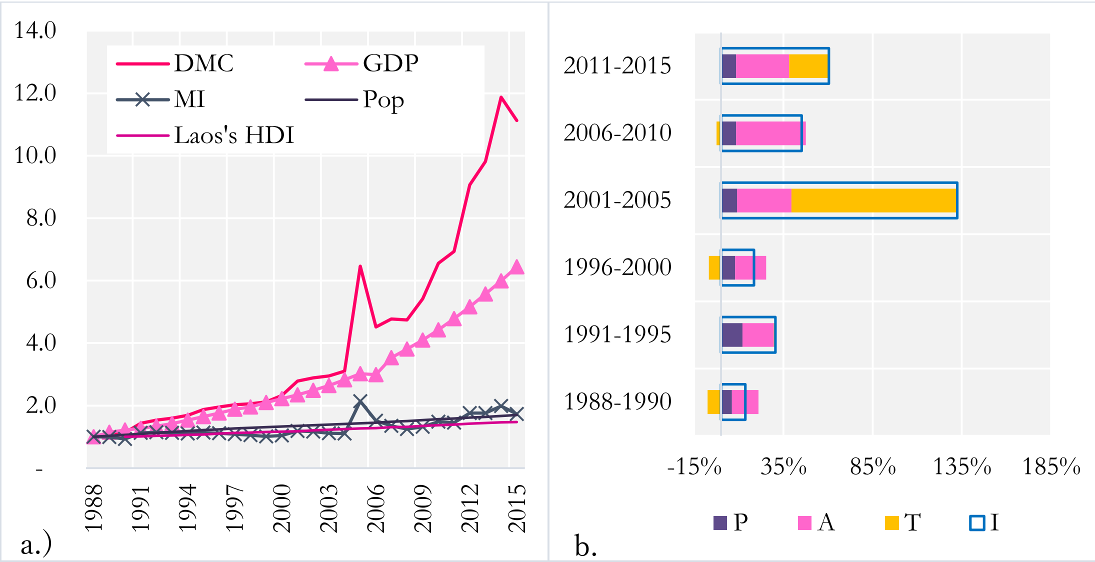


Figure 6-3.a. Trends in selected indicators (Index 1988 = 1), b. IPAT analysis of materials use in Lao PDR

IPAT is a simple analytical framework that helps uncover broad driving factors of environmental impact. IPAT was developed by Ehrlich and Holdren (1971) and aims to explain the impact on the environment of a process or economic activity (I) as the product of population (P), affluence (A), and technology (T). As proposed by Schandl and West (2010), I is defined as the total DMC, A as GDP per capita, and T as DMC per unit of GDP. I transformed the IPAT equation to a logarithmic form following the methodology proposed by Herendeen (1998).

To identify drivers for the rapid increase of DMC (I) I used the IPAT analytical framework (I = P*A*T). This shows the extent to which population growth (P), affluence (A), and technological development coefficient (T) contributed to or mitigated DMC growth. I divided the time series into six 5-year periods which corresponded to the Five-Year National Socioeconomic Development Plans of Lao PDR (NSEDP) prepared by the Ministry of Planning and Investment. Throughout all periods, population and affluence contributed to increasing domestic material consumption with affluence (growth in per-capita GDP) being the most important factor (see Figure 6-3b). During 1988–1990, coinciding with the 2nd NSEDP at a time when the Lao socioeconomic system was transforming from a centrally planned system to a more market based system through the introduction of the New Economic Mechanism in 1986, DMC grew by 14%, mainly driven by increases of P and A and offset by some improvement in resource intensity.

From 1991 to 1995, all three factors played an important role in contributing to a 31% increase in DMC. From 1996 to 2000, P and A continued to drive total material consumption but with a small offset achieved through technological improvement. The years 2001 to 2005 signified the onset of an acceleration period of material consumption in Lao PDR with a total increase in DMC of 132%. In this period, the increase in material consumption was mainly driven by a large increase in the resource intensity (T) of the economy coupled with the consistent contributions of P and A. The years 2006 to 2010 were a period of reprieve, reflecting global economic conditions, but from 2011 to 2015 the Lao economy was back on a material growth trajectory of 61% of DMC. The increase was fueled by population and consumption growth and further industrialization, with the transition from traditional to modern society i.e. from a biomass-based agricultural economy to a minerals-based industrial and urban economy, leading to higher overall resource intensity of the economy.

6.4 EW-MFA results for Policy Implications in Lao PDR

This dissertation tries to improve the EW-MFA accounting for developing countries and also show how to use the obtained results for sustainable resource management in those countries, with the case study for Lao PDR in this chapter. The resource efficiency analysis shows the importance of resource governance and well-tailored policies to increase the benefits and mitigate the costs of the Lao development pathway.

The rapid development of mining and resource extractive activities to support the economic development in Lao PDR push the tensions to environment in various domains such as environmental impacts including large-scale land use change, toxic pollution and land degradation. Currently, the regulation and governance related to environmental impacts and pollution control are in the early stage of development. Considering the flows related to mining activity have been emerged as shown in Chapter 4, the Lao government may consider strengthening regulation and governance for the fast-growing mining sector.

There are similar issues with regard to energy generation. Lao PDR has abundant potential for hydropower generation but most of the electricity generated is supplied to neighboring countries, leaving only about 25% for domestic consumption. In 2014, total installed capacity of hydropower plants was 3,335 MW with approximately 88% belonging to independent power producer private companies (Ministry of Energy and Mines of Lao PDR 2015). Undoubtedly, electricity generation has been an important contributor to socioeconomic development in Lao PDR as a whole, but it comes at the cost of decreased forest cover area (70% in 1940 to 40% in 2010; World Bank (2017a)), loss of biodiversity, and socioeconomic impacts such resettlement from the reservoir area, and other environmental impacts during the construction period. It is still questionable whether energy generation will contribute to sustainable economic development. This has been a challenge for policymakers in Lao PDR, to design innovative policy that helps minimize environmental problems and maximize benefits from this natural resource-based income to society in order to achieve the NSEDP and graduate from being a least-developed country by 2020.

One important issue for the Lao economy is to create options for value-adding and domestic manufacturing based on the large potential for primary materials from mining and agriculture. There are ample opportunities for secondary industries which would allow for higher incomes and a greater contribution to the Lao economy than current extractive and primary export-oriented sectors allow for. More value addition could occur in several sectors of the Lao PDR economy and would profit from the availability of metal resource in combination with affordable electricity, timber and non-timber forest products. Investments to build secondary industries to the mining, forestry and agriculture sectors would provide new employment, better incomes for workers and greater benefits to the Lao national accounts compared to the current sole focus on primary resource and electricity exports.

Especially the rich biological diversity of Laos and the usability of those rich biological resource for medical and cosmetic industries could be additional sources of value addition. There is additional potential in tourism and eco-tourism which need be exploited to build a diversified economy which is less susceptible to fluctuation in global demand for and world market prices of primary materials and energy. Such more diversified strategy to economic development would rely on training and capacity building of workers, upskilling of industrial leadership and would also increasingly offer opportunities for resource efficiency and recycling through improvements in eco-efficiency of the emerging secondary industries.

The Lao PDR does not have strong competitive advantage with regard to building sophisticated industrial and manufacturing operations at this time but could set itself up for the growth of its secondary industries leveraging the rich resource endowment as a first step to a more diversified economic future.

Building a more diversified industry will help avoid economic vulnerability. Recent modeling (Hatfield-Dodds et al. 2017) shows that in a global economy guided by ambitious policies for resource efficiency and greenhouse gas abatement, countries which rely on primary resource exporting as a main component of their economic development and are currently low-income economies would lose economic growth and employment. Because such global policy settings are now more likely with the Paris Agreement on Climate Change in place and the Sustainable Development Goals accepted, economic diversification is fundamental to Lao PDR's future economic prosperity.

Industrialization, urbanization and mining have also contributed to new industrial and household waste flows which overwhelm current waste management and recycling policies and capacities. Air pollution is another important new feature of the growing Lao economy. Managing waste and emissions will require well-designed policies and programs, and new infrastructure for waste collection and recycling to manage the ever-growing amounts of waste and fast-changing levels of toxicity and pollution (UNEP 2017b). The nascent manufacturing industry will profit from investment in clean production and the Lao government needs be commended for its interest and investment in green economic development (Ministry of Planning and Investment of Lao PDR 2016). While other emerging economies in Southeast Asia have used their manufacturing growth to invest in resource efficiency and waste minimization, such policy strategies are still rare in Lao PDR (Aoki-Suzuki 2015).

CHAPTER 7
The Weight of Developing Country through dynamic MFA, Case study of Lao PDR

7.1 Introduction

The Earth provides resource for human to build up infrastructure that provides services to society. What is left behind is waste and emissions that will roll back to the environment. Human activities involved materials, energy and emissions interaction with the environment. Recent study shows that since the beginning of 20th century until now, the global material stocks that serve the human well-being has increased more than 23-fold (Krausmann et al. 2017). This would lead to four-fold increase of the global material stocks in 2050, and carbon dioxide emissions will surpass the climate change goal target (Krausmann et al. 2017).

The understanding of materials throughputs suggests that currently more than half of input materials is accumulating in the society (Krausmann et al. 2017), which is refer to the term "in-use material stocks" (hereafter "stocks" or "material stocks"). Stocks provides services for society such as shelter, mobility, communication and could be considered as human well-being measurement matric (Pauliuk and Müller 2014). The level of stocks plays a crucial role in the determination of the sustainable development pathway as the stocks required materials and energy to provide such services and to maintain its function. The stocks can also directly be linked with the potential future waste to be released from society at the end-of-life period of stocks (Müller et al. 2014).

Underlining such important features and the contribution of stocks to sustainable development, this raises the needs of comprehensive understanding of stocks (Müller et al. 2014). The composition of in-use stocks varies among cities, countries, region, depend on living lifestyle, infrastructure systems, and industrial systems. There are several studies of material stocks in European countries (B. Müller 2006; Bergsdal et al. 2007; Kleemann et al. 2017), Japan (Fishman et al. 2014; Hashimoto et al. 2007) , United State (Zeltner et al. 1999), Korea (Park et al. 2011), China (Zhi et al. 2018), as well as global level (Krausmann et al. 2017) that employed dynamic MFA to assess the flows and stocks and its environmental implications.

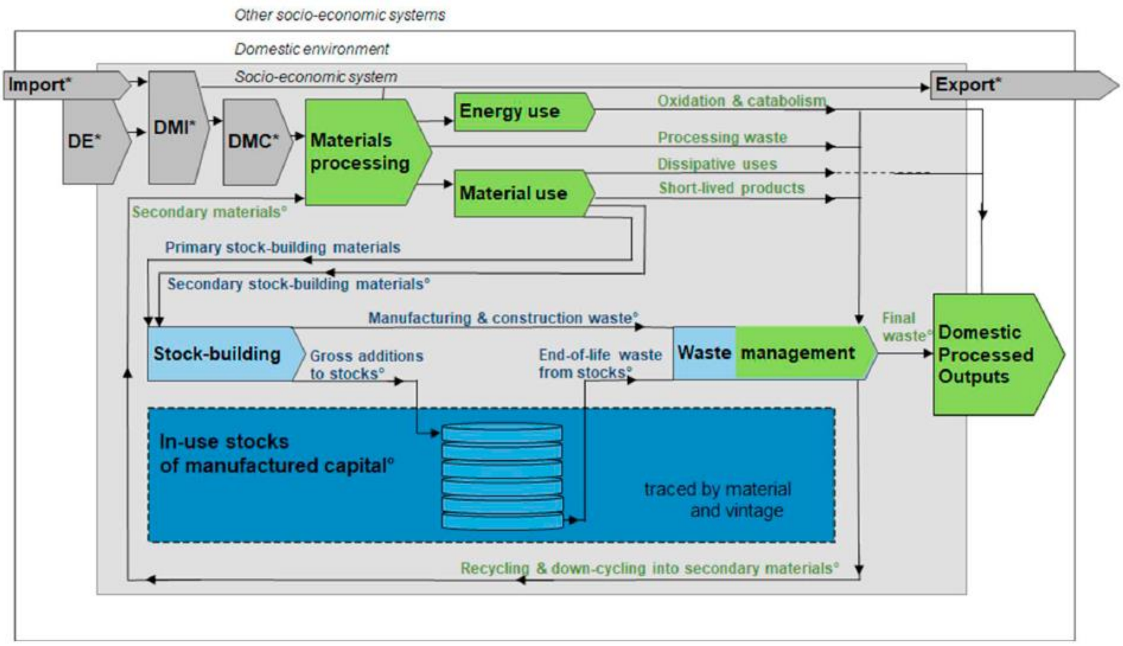
For developing countries, case studies of dynamic MFA to quantify the weight of an economy rarely exist. This is due to the availability of statistical data, lack of human resource, and last but not least, the understanding of usefulness of the dynamic MFA results. Several studies have shown that the better understating of stocks would provide valuable information for developing circular economy, strategic planning for urban-mining, solid waste management, as well as dematerialization (Müller et al. 2014).

Inflows of materials into the socioeconomic system could be considered into certain major categories based on their functionality such as stocks building materials, technical energy, food and feed, and other dissipative uses materials (Krausmann et al. 2017). Dynamic MFA is extended MFA that of considered the dynamic behavior of resource throughputs, a life time of certain materials or products. Dynamic MFA provides historical, present, and future pattern of materials throughput. Dynamic MFA grants the access to the information on inflows, materials stocks, and outflows. There several approaches for quantifying the stocks and flows based on dynamic MFA, such as (1) top-down approach (Fishman et al. 2014; Krausmann et al. 2017; Liu et al. 2012), (2) bottom-up approach, (3) demand-driven approach (Bergsdal et al. 2007; B. Müller 2006; Zhi et al. 2018), and (4) geographical information systems (GIS) (Kleemann et al. 2017; Tanikawa and Hashimoto 2009) , and (5) remote sensing (Liang et al. 2014). In this chapter, based on the inflows data from EW-MFA of Lao PDR in Chapter 4, the dynamic MFA is tried to accelerate, for the first time, the understanding of the weight of developing nation through tonnage of resource that accumulated in the society.

7.2 Methodology of Dynamic MFA modeling

The dynamic MFA modeling in this study is based on the MISO (Material Input, Stocks and Output) model, which developed based on the expansion of the EW-MFA by considering the dynamic behavior of the material inputs (Krausmann et al. 2017; Wiedenhofer et al. 2019). The MISO model is dynamic top-down inflow driven model with respect the principle rule of EW-MFA, mass-balanced (Fishman et al. 2014; Müller et al. 2014; Glöser et al. 2013; Krausmann et al. 2017).

The materials input into the model was taken from the EW-MFA conducted in previous chapter. Based on the system boundary of the model (see Figure 7-1), the DMC of EW-MFA is differentiated into four categories based on its functionality, stocks building materials, technical energy, food and feed, and other dissipative uses (Krausmann et al. 2017; Wiedenhofer et al. 2019).



Source: Wiedenhofer et al. (2019) (Remark: This is an open access article under the CC BY license)

Figure 7-1 The system Framework of MISO Model

The studied period is set as the same with EW-MFA 1988 to 2015. In order to properly accounted for the dynamic of the material inputs during the studied period, the spin-up period has to be considered to estimate the initial in-use stocks and the end-of-life outflows at the initial year of this study (1988). Based on the assumption of the longest lifetime of the material input (50 years for wood for construction, see Annex 2), the beginning of the spin-up period is assumed to be year 1938. During the spin-up period, the average materials input per GDP during the beginning of studied period is used to back-casting the materials input with the GDP data from the Maddison Project (Bolt and van Zanden 2014). The details for the models could be found in these literature (Krausmann et al. 2017; Wiedenhofer et al. 2019)

7.3 Sociometabolic transition based on Dynamic MFA

Figure 7-2 shows the evolution of materials stocks in Lao PDR from 1988 to 2015. Within three decades, materials stocks in Lao PDR grown almost 7-fold, increased from 100.4 million tonnes to 725.7 million tonnes with annual growth rate of 7.6% between 1988 to 2015. The annual growth rate is faster in the last decade (2000 to 2015) at 9.1% per year. The iron increased with the fastest growth rate of 29.3%, followed by other metals as 22.6%, industrial minerals as 17.2%, and 14.5% for non-metallic minerals for construction. The growth rate of timber was the slowest with average growth rate of less than 1% per year.

In the beginning years of studied period, wood for construction accounted for most part of stocks (more than 84% of total in-use stocks). The transition of composition of stocks took place around 1990s, which is now the non-metallic minerals for construction dominated the whole part of the in-use stocks (accounted for more than 83% of total in-use stocks). The global share of this material category in year 2010 was 79% (Krausmann et al. 2017).

Figure 7-2.b to Figure 7-2.e shows the breakdown of stocks by four main materials, includes timber, iron and construction materials, iron, and industrial materials. The increasing trend of timber is quite stable throughout the studied period. The stocks of timber increased from 84.7 million tonnes in 1988 to 108.4 million tonnes in 2015, approximately by factor of 1.3. Other materials increased exponentially. The non-metallic minerals for construction increased by factor of 38.8 compared to the based year 1988. This material contributes to the majority of the in-use stocks in 2015 with total amount of 601.7 million tonnes. Iron and industrial minerals increased even more faster than the construction materials. The slow increasing rate of timber and fast increasing of other materials indicating that there has been a shifting of materials use for building infrastructure system in Lao PDR.

In Figure 7-3.a, the results show that there are slightly decreasing trends of stocks per capita of timber, but stocks per capita of non-metallic minerals for construction sharply increased. This is another evidence (supporting the results of EW-MFA) that the resource use in Lao PDR is dominated by the accumulation of infrastructures. The growth pattern of total stocks per capita of Lao PDR is following other developing countries, but during the last decade it already outpace the level of other developing countries in the rest of the world (see Figure 7-3.b). Comparing to the average level of global stocks per capita in 2010, with the current rate of accumulation, the level of stocks per capita of Lao PDR is likely to surpass the global level soon. However, when compared to industrial countries, the level of stocks per capita of Lao PDR is relatively low. This is a very good opportunity for the country to leapfrogging the resource use to optimal saturation level by increasing resource efficiency through system-wide policy design, technology advancement, and innovations

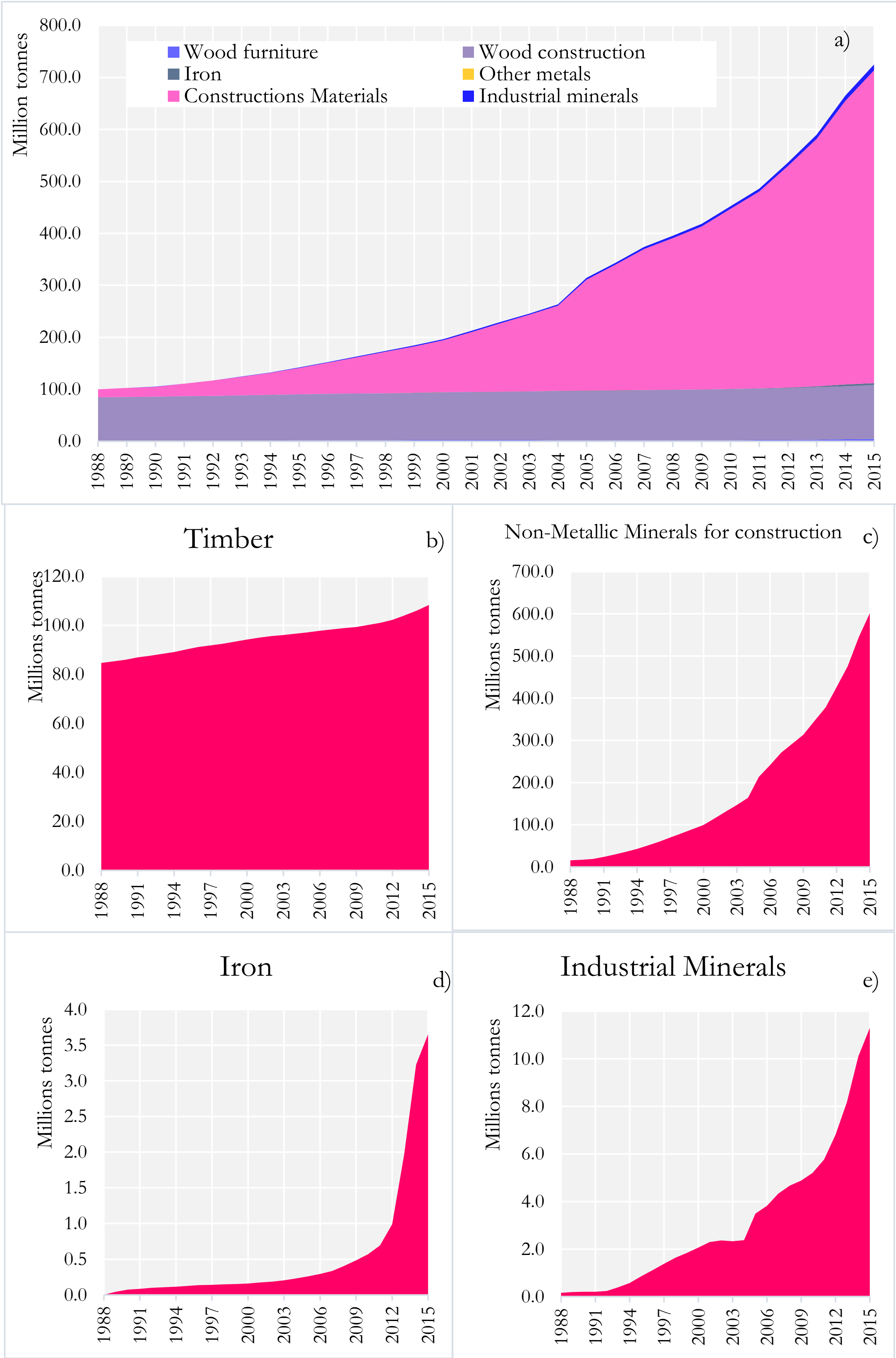
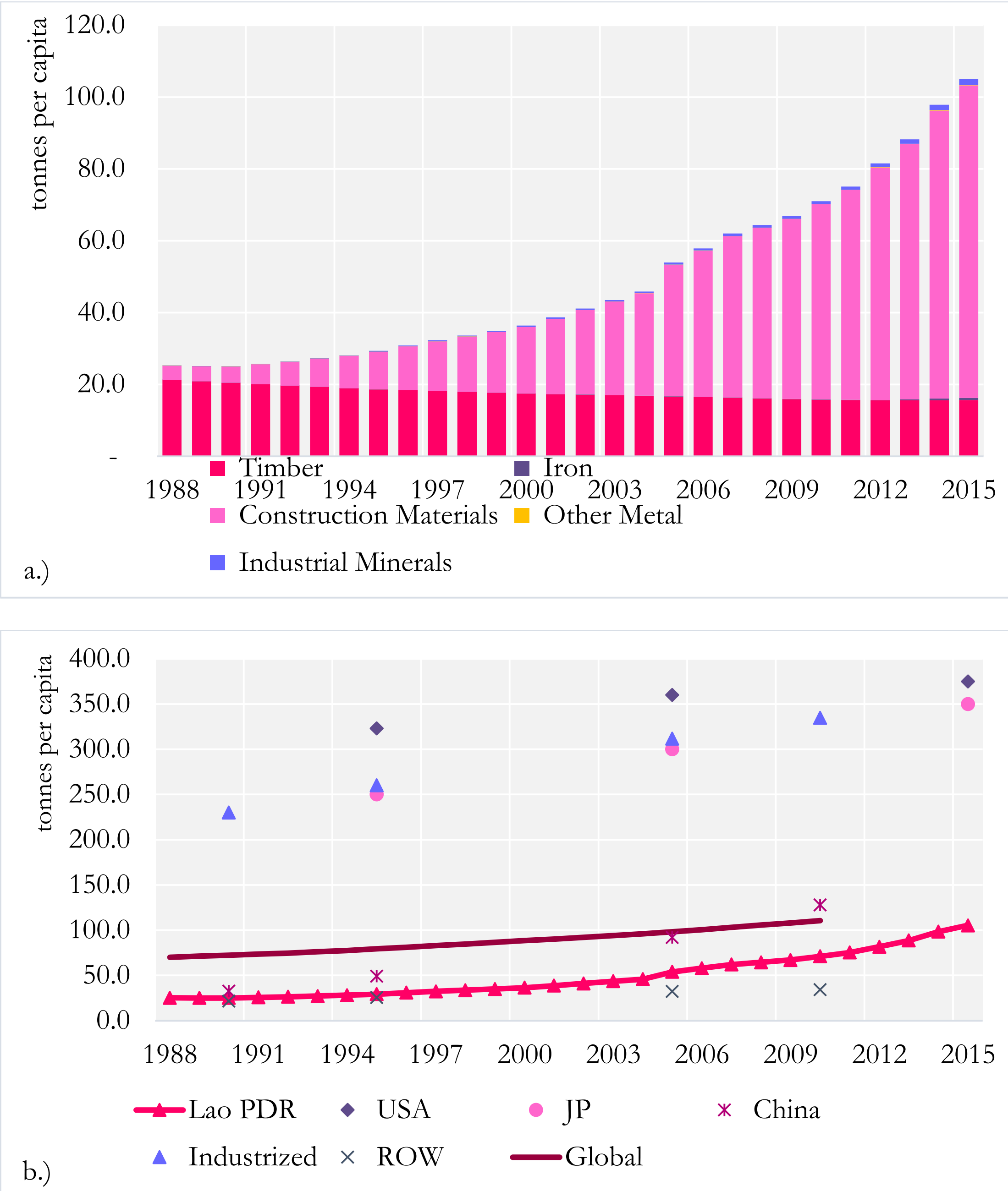


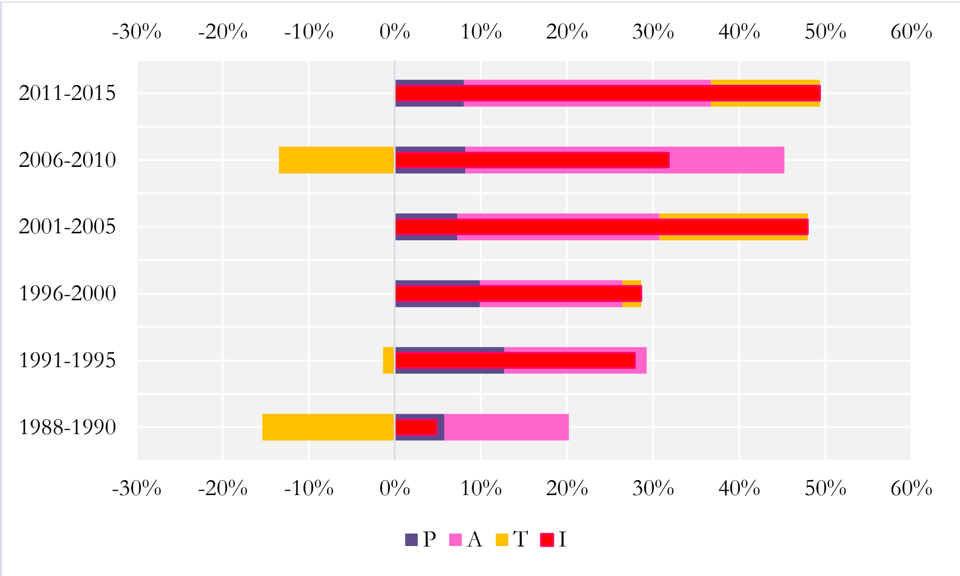
Figure 7-2 Material stocks in Lao PDR from 1988 - 2015



Source: USA and Japan data from Fishman et al. (2014); Industrial, China, Rest of the World (ROW), and Global data from Krausmann et al. (2017).

Figure 7-3. a) In-use stocks per capita by main materials categories of Lao PDR; b) In-use stocks per capita of selected countries and global

The IPAT analysis shows that the affluence (GDP) has been a main driver of increasing of the material stocks in Lao PDR throughout the studied period (see Figure 7-4), which is similar to the case study of Japanese's prefecture (Fishman et al. 2015). Due to slow population growth rate of the country, population is seemed to be less influenced the accumulation of the stocks for this case study. The stocks accumulation is very important for developing countries in terms of building up infrastructure and capital. The analysis of growth patterns of selected countries show that the accumulation rate of all important materials for stocks-building (Steel, cement, aluminum, copper) has been on the rise for the emerging economy liked China and saturate for four industrial countries (Germany, Japan, the United States, United Kingdoms) (Bleischwitz et al. 2018). The study shows that the saturation of stocks accumulation happened when the GDP reached $12,000 GDP/capita for steel and cement, and at level of $20,000 GDP per capita for copper (Bleischwitz et al. 2018).



Note: I-In-use stock, P-Population, A-Affluence, T-Stocks per GDP

Figure 7-4 IPAT Analysis of Material Stocks in Lao PDR

The NAS, by Eurostat's definition, is the indicator that measures the growth of physical stocks in a society. The NAS could be calculated by balancing the EW-MFA or derived from the dynamic MFA, MISO model. In Figure 7-5, the results of NAS from EW-MFA and MISO model are compared. As mentioned in Wiedenhofer et al. (2019), elaborating the in-use stocks based on the EW-MFA's results engage high uncertainty and lack of comprehensive information of the stocks (for instance the composition of NAS could not be drawn from the mass-balanced approach). The comparison shows that the results from MISO model is lower. The difference might be due to the missing of bulky amount of the waste from end-of-life outflows of materials mainly used for construction in the DPO of EW-MFA. However, comparing the percentage of NAS/DMC of these two results to the comprehensive global stocks study (Krausmann et al. 2017), the results from MISO model seem to be more consistent and reliable. In the case that the data is sufficiently available, the modeling of stocks based on the dynamic MFA model, the MISO model, is more preferable and the comprehensive understanding of the stocks and outflows could be revealed.

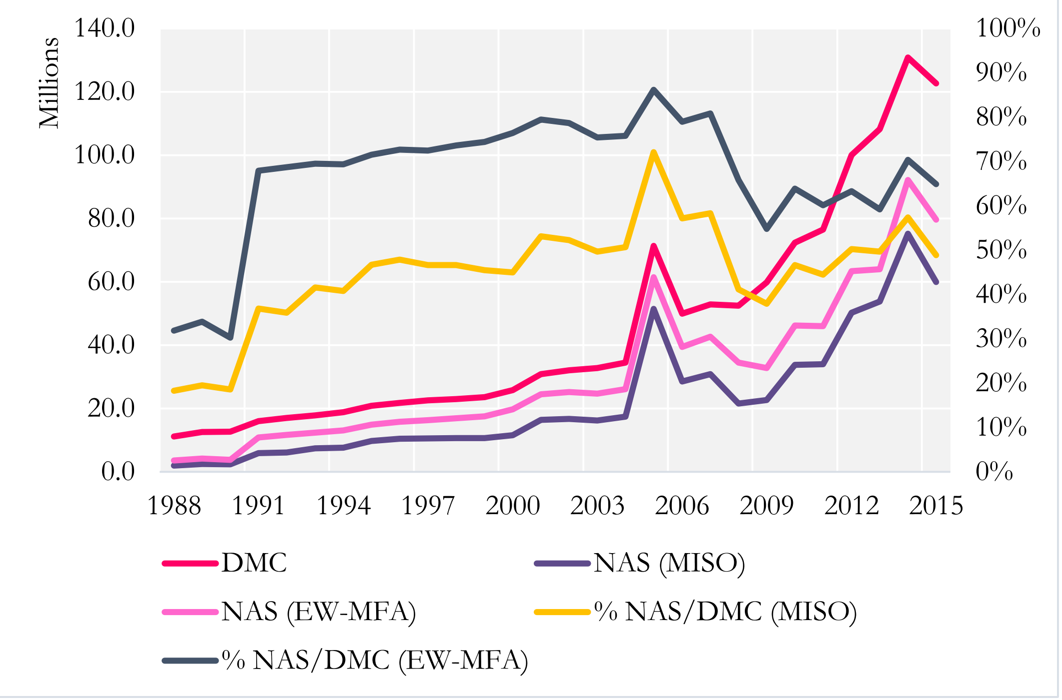


Figure 7-5 Comparison of NAS between MISO model and EW-MFA model, and the sharing rate of stocks by total DMC (right axis)

CHAPTER 8
Conclusions and Recommendations

8.1 Summary of the previous chapters

The Industrial Ecology, especially MFA, is an important framework for sustainable resource management. MFA is now believed already matured and has been applied to provide evidence based information for sustainable resource management across the globe. The review of the evolution of Industrial Ecology research in ASEAN, which majority of the member countries are in the stage of developing economy, showed that LCA research is the popular research topic in the region. LCA studies are focusing on topics of renewable energy production from biomaterials, aquaculture industry, solid waste management technology and energy consumption in the building. Input-Output analysis, one of the fundamental techniques Industrial Ecology, has a long history in the region. The first study of IOT in ASEAN countries could be traced back to early 1970s. Other two disciplines, MFA and Urban Metabolism, show slow progress with the total number of only less than 7% of total Industry Ecology publications related to ASEAN, which means there are knowledge gaps to be fulfilled. MFA was selected as the main research topic of the dissertation aiming to improve the methodological details to provide more accurate information for sustainable resource management of developing countries in the region.

The Eurostat's MFA guideline was used as the main compilation guideline for conducting the EW-MFA of the case studies. The limitations of implementing Eurostat's MFA guideline, which was specifically developed for European countries, were discussed and the methodological improvement were proposed. In this dissertation, the potential data sources for compiling EW-MFA were given based on the suggestion of Eurostat's guideline and the hands-on experiences gained when EW-MFA of the case study was conducting. The estimation approaches for missing data in the statistics were developed based on local knowledge, civil engineering background, and literatures. The methodological improvements in this study include estimation approach for grazing biomass, the developed material intensity of sand and gravel used in concrete production, employing the direct accounting for metal ores, constructing trades account based on the integration of national statistics and UN COMTRADE database, and estimation of domestic processed output. The methodologies for handling the uncertainty of the EW-MFA were introduced based on the available knowledge in the literature.

The improved EW-MFA framework for developing country was then applied to conduct the full balance EW-MFA of Lao PDR. The results provided new insight into the resource use of Lao PDR. The results indicated that by utilizing the local knowledge and national statistics, more realistic EW-MFA results could be obtained and could be further used in the national policies design. Main EW-MFA indicators of Lao PDR during 1988 to 2015 were obtained including Domestic Extraction, Imports and Exports, Direct Material Input, Domestic Material Consumption, Domestic Processed Output, and Net Addition to Stocks. The snapshots of full EW-MFA were depicted for year 2010, as the based year of resource use acceleration, and 2015, as the representative of current trends. The uncertainty of the results was also discussed and the critical source of uncertainty were identified. Then the results of this study were compared to UNEP IRP's database for selected indicators (UNEP IRP 2018b). Additionally, the comparison of some important EW-MFA indicators was compared between direct material flows and upstream material requirement (Raw Material Equivalent) to show the potential variance when using different perspective to report the EW-MFA results.

To test the improvements that proposed by utilizing the local knowledge and national statistics with the case study of Lao PDR, the methodology was implemented for another developing country, Bangladesh. The headline EW-MFA indicators were derived from the model. This is for the first time for the Bangladesh that EW-MFA is compiled based on the national statistics and local parameters. The results showed the significant improvement, especially for accounting of non-metallic minerals material, which seems to be significantly under-estimated in the IRP's database.

The resource efficiency concept and its implication for sustainable development policy design were discussed. From the results of resource efficiency analysis, the recommendations for policy implication for Lao PDR were provided. The IPAT framework was applied to identify the main drivers of resource use of the country in different periods.

To better understand the composition of the resource accumulated in the nation's socioeconomic system, the state-of-art dynamic MFA, based on MISO model

(Krausmann et al. 2017; Wiedenhofer et al. 2019), was conducted. The results provide a more detail understanding of the material stocks accumulated in the society to provide services for the socioeconomic development.

This study provides two-fold contribution to the society. First is the methodological improvement of EW-MFA for developing country and second is the evidence-based information that could be used for sustainable resource management policy design. The future works to improve the limitations exist in this study were discussed.

8.2 Contribution of the dissertation to society

8.2.1 Methodological improvement

This dissertation is for the first time that the EW-MFA of developing country is conducted based on the nation's own statistical data and the local knowledge on estimating the missing data in the statistics. This provides new insight into the understanding of resource uses in developing world. The EW-MFA was compiled based on the state-of-art knowledge of EW-MFA.

On the one hand, rather than the contribution to the new knowledge of resource use in developing world, the dissertation furthermore contributes the methodological improvement for compiling EW-MFA of developing countries. Specifically, the significant improvements cloud be summarized as following:

- estimation of crops residues based on the regional data parameters
- estimation of grazed biomass based on developed national parameters
- developed the new material intensity of sand and gravel used for concrete production
- integrated the trades data from national statistics and international database to construct the trades account for developing country
- demonstrate the DPO compiling for developing country, which data based on the estimation and international database

- demonstrate how to handle the uncertainty the model results based on the state-of-art approach, "Monte Carlo Simulation", and the general approach "Gaussian Error Propagations"

8.2.2 Indicators for policy design: Green-growth strategy in Lao PDR's Five-Year National Socio-Economic Development Plan and SDGs reporting

The results from this dissertation could provide two-fold benefits for Lao PDR as the indicators to measure the progress for national sustainable resource management as well as the indicators for benchmarking and reporting the progress of the SDGs.

Lao PDR's socioeconomic development is mainly relied on the Five-Year National Socio-Economic Development Plan. In the recent 8th Five-Year National Socio-Economic Development Plan (8th NSEDP), the "Green-growth" is set as one of three main expected outcomes of the plan and specific target mentioned is to "create mechanisms to support the implementation of the National Green Growth Strategy". However, the principal framework and indicators for implementing are still under development.

From the EW-MFA, the information derived from model could be adopted as the indicators for such strategy. For instance, resource efficiency indicators, which could be measured as resource productivity or resource intensity, could be considered as the lead indicator to measure how efficient the resource are used to generate GDP. These indicators have been used in sustainable policy design in many parts of the world, notably cases are the European Resource Efficiency Score Board, Sound Material Cycle Societies of Japan, and the Circular Economy in China. Lao PDR could utilize the framework proposed in this study or even attempt to improve the results from this study and directly used as the measuring indicators for its National Green Growth Strategy.

At the global level, Lao PDR, together with other more than 150 countries, adopted the Sustainable Development Goals (SDGs) in 2015 aiming to progress forward together toward the sustainable development for all and leaving no one behind. Lao PDR is strongly committed to the 2030 Agenda for Sustainable Development in the implementation and achievement of the SDGs. On 20 September 2017, the Presidential Degree on set up The National Steering Committee for SDGs implementation was enacted which chaired by the Prime Minister aligned with committee members from all concerned ministries and agencies (The Government of the Lao People's Democratic Republic 2018). Lao PDR is one of the frontrunner that implemented and localized the SDGs into the national development plan. In the current the Five-Year National Socio-Economic Development Plan (NSEDP), the 8th Five-Year National Socio-Economic Development Plan (8th NSEDP), nearly 60% of its indicators are linked to SDGs. The chair committed that the remaining SDGs indicators would be integrated into 9th NSEDP and 10th NSEDP. Recently on during 16-18 July 2018, the 1st Voluntary National Review on the Implementation of the 2030 Agenda for Sustainable Development was presented by Minister of Foreign Affairs of Lao PDR at UN High-Level Political Forum along with other 47 Member States (United Nations in Lao PDR 2018).

In the report (The Government of the Lao People's Democratic Republic 2018), the country shows some progress on all SDGs but the implicit indicators for measuring the progress have not yet existed for many SDGs targets. The feedback survey conducted during the National Consultation on the Voluntary National Review on the Implementation of the 2030 Agenda for Sustainable Development also shows that the stakeholders' perception of the progress made by Lao PDR towards the SDG 8 and SDG 12 had the lowest score (The Government of the Lao People's Democratic Republic 2018), which could infer that that the evidence-base information is needed for such SDGs in order to show the quantifiable progress.

The results from EW-MFA presented in this study would help to improve the capacity of Lao PDR to report progress on the implementation and success of the Sustainable Development Goals (SDGs). Material flow indicators from this study could be used to report against targets 8.4, 12.2 and 12.5 of the SDGs. Following paragraphs are some example for implication of EW-MFA for reporting SDGs.

From the EW-MFA results, Lao PDR, on its current trajectory, is more likely to fails on target 8.4 which requires countries to continuously improve resource productivity of production and consumption. The trend in Lao PDR of decreasing resource productivity does not meet the aspiration of SDG 8.4.

For the Target 12.2, it requires sustainable management of natural resource and needed to be monitored. This target could be measured by using DMC per capita.

Sustainable management of resource would require DMC per capita to be below the empirical observed threshold level which has clearly been surpassed by the Lao economy.

Target 12.5 asks for waste reduction and an increase in the recycling rate. To the extent that fast-rising DMC must also be interpreted as a proxy for increasing waste flows Laos also fails on this target. Since an assessment of the output side, in detail, of Lao material flows has not been undertaken for this study, it is hard to judge whether the recycling rate of the Lao economy has been improving, although an overall reading of environmental pressures from the input accounts would suggest otherwise.

8.3 Recommendations for future works to improve EW-MFA accounting in developing countries

8.3.1 Which account should be prioritized?

EW-MFA framework has matured in the recent years (Fischer-Kowalski et al. 2011). However, limitations for EW-MFA has remained to be solved, especially for developing countries. EW-MFA is based on the principle of the mass balance. It consists of several individual accounts. In this sections, some of the recommendations for EW-MFA compiler in developing country are addressed, which EW-MFA account should be prioritized based on the experiences in compiling the EW-MFA of the case studies in this dissertation.

The accounting of the DE is very first step of conducting EW-MFA. Thus, regarding this aspect, the highest prioritized account should be DE. Rather than that, DE of many developing countries accounted for more than 90% of total direct material inputs into the socioeconomic system (Xu and Zhang 2007; Martinico-Perez et al. 2018a). These two reasons could at least emphasize how DE accounting could be considered as the important account to be started with.

To measure the resource efficiency, quantifying the DMC indicator is mandatory. In order to reach the value of DMC, based on the EW-MFA accounting's rule, the imports and exports of resource and products have to be known. Thus, another important account after DE is a physical trades account. By completing this account, not only DMC could be derived but PTB indicator as well. However, due to the limitation of the data availability, this account is normally involving various estimation approaches and high uncertainty is obvious attached. Compiler should always recognize the uncertainty when constructing the accounts.

In order to complete the full mass-balance EW-MFA, the quantity of DPO and balancing items needs to be known. The compiling of DPO, even in the developed countries, is a difficult task. This is due to the availability of waste and emissions statistics and systematic framework (Schandl and Miatto 2018; Wiedenhofer et al. 2019). Fortunately, the most recent Eurostat's EW-MFA guideline attempted to harmonized the methodology for compiling the DPO and balancing items (Eurostat 2016). As the outcomes of the publication of the guideline, currently there are some recent studies demonstrate the possibility of conducting the full comprehensive EW-MFA in developed (Schandl and Miatto 2018) and developing countries (Martinico-Perez et al. 2018a; Vilaysouk et al. 2018). However, all these studies heavily relied on the international dataset for conducting DPO account, which left the room for the uncertainty to exist when utilizing the international datasets. The international database for compiling this account should be carefully chosen.

8.3.2 Which materials should be prioritized?

Considering four main material categories (namely biomass, metal ores, non-metallic minerals, and fossil fuels and energy carrier materials) in total DMC, the non-metallic minerals for construction (mainly are sand and gravel, clay, limestone, gypsum) are the most important material to be prioritized when conducting EW-MFA for several reason.

First, non-metallic minerals are the main material used in the construction of building and infrastructure and at the global level it accounted for more than 50% of total global resource use (Miatto et al. 2017) and even higher in the developing country which the results of this study showing that it accounted for more than 70% for some years when there are mega construction projects. The non-metallic minerals are the main driver of resource consumption and will remain as the most dominant material in DMC for next several decades, especially in developing countries where building, infrastructure and capital for production are still insufficient.

Another rationale is that the official statistical data of this material category is not well record in the statistics system, both in developed and developing countries, due to its cheap price and abundance existence, and has to relies on estimations (Miatto et al. 2017). Applying the civil engineering knowledge to estimate the amount of global non-metallic minerals demonstrates that the precision of the estimation could be improved (Miatto et al. 2017). In this study, I also applied the similar principle to develop the coefficient to improve the estimation of sand and gravel use from cement consumption data based on the local construction standard for concrete mixing of the studied country, Lao PDR (see section 3.3.2).

Another important sub-category of non-metallic minerals is clay and kaolin which is the important raw material to produce brick, tiles and ceramic. Based on the most comprehensive study of global non-metallic minerals use, this subcategory is accounted for approximately 16% of total non-metallic minerals. Because of its importance in construction of buildings/infrastructures in developing countries, this subcategory material should be prioritized as well. The estimation of clay and kaolin required to produce the bricks in the case study for Bangladesh, showed that utilizing the national figure yield the result higher than the one recorded in the international database more than factor of 7.

Besides the important of massive volumetric of the non-metallic minerals, another concern regarding this material category is the importance in its accumulation rate as the in-use stocks in the society. Most of the non-metallic minerals, especially ones mainly used for construction, likely to stay in the socioeconomic longer. The accumulation of these materials would require energy, materials to maintain and operate. Thus, considering these aspects, the accounting for non-metallic minerals is crucial.

The accounting of metal ores is currently estimated based on the conversion from metal content or metal concentrate to gross ores. This approach involved high uncertainty regarding to high variation of ore grades across the locations. For countries that the DE of metal ores is comparatively small when compared to other materials, this simple approach could be utilized for the sake of limitation resource and capacity. However, for the extractive country like Australia or Chile, if the conversion approach has to be applied, estimating site-by-site should be considered. In this dissertation, the implementation of direct accounting based on mine operation data approach is proposed. This direct accounting could help in reducing the uncertainty.

For the biomass, currently national statistics and international statistics now cover most of the crops production. However, the grazing biomass and crops residues still have to rely on the estimation. The study show that local parameters have influenced the total EW-MFA results. From the literature it shows that the parameters used in estimating these flows varies country-by-country and region-by-region. The statistics recording systems could be update to include these flows if it large.

Fossil fuels and energy carrier material are well recorded both in national and international database. Thus, the accounting of this material could be considered as the most complete and reliable in EW-MFA.

8.3.3 Which statistical data should be improved?

As mentioned, agriculture production has been well-recorded in the statistics. However, the amount of crops residues and grazing biomass are often missing in the official statistics. In order to increase the precision of the accounting for the biomass, crops residues and grazing biomass should be considered to be included in the official statistics system.

Regarding production data of mining sector, it is now already included in the official national statistics system for many countries. However, the figure is generally reported as the metal content or concentrate. Thus, improving the reporting system for mining sector by including more inclusive information such as overburden, total ore processed, ore grade, coupled-products, for instance. These parameters vary among the individual sites. Therefore, this could improve the precision of the accounting for metal ores.

For non-metallic minerals, due to its low price and relative abundance (for the case of sand and gravel), is currently missing or under-report in the statistics. The improvement of the statistics reporting system would significantly contribute to reduce the uncertainty of the EW-MFA due to its majority sharing in many EW-MFA indicators. But even in the case that the estimation is needed. Improving the Industry Production statistics reporting format could help to identify the products that needed for such estimation straightforwardly.

Import-export statistics in developing countries are generally poor, especially when considering the physical weight of the commodities. However, for many developing countries, these two flows seem to be relatively small when compare to the DE. But improving the statistics reporting systems by attaching the physical units to each transaction could provide the information for other strategic analysis for instance to analyze the security of supply chain of specific metals, rare earth elements etc.

8.4 Recommendation for utilizing MFA results for sustainable resource management policy

Firstly, I would like to started the discussion for this recommendation section by quoting the statement of the First Vice-President of the European Commission and responsible for sustainable development, Frans Timmermans, in the 2015's Sustainable development in the European Union Report: "You cannot manage what you don't measure".

The meaning of the above statement is straight forward, inferring that for every country, in order to develop sustainable development policies at least proper indicators should be defined and comprehensively reflecting the situation in such countries. As discussed in many places throughout this dissertation, EW-MFA results could provide information for such sustainable resource management policy design and they have been already utilized across the globe at various levels.

The fundamental steering iterative processes to move toward sustainable resource use suggested by IRP (2017) comprise of 1) monitoring, 2) set targets 3) test and innovate, and 4) learn and evaluate.

Source: IRP (2017)

Figure 8-1 Iterative steps to move toward sustainable resource use

1) Monitoring: Based the comprehensive MFA of this study, the results could be used to support for the first step for "monitoring" the state of environment and accounts for resource use and other flows looking toward the sustainable development.

2) Set targets: Next step is setting the targets, which rise the question "What number or quantity should be considered as the targets?". This is very difficult question that could not be precisely addressed in this dissertation. However, at least the scientific evidence base information delivered in this dissertation, accompanied by additional participations from other stakeholders could turn into this information into the practical policy targets.

3) Test and Innovative: This step required the intervention of both markets and government on the technology and market system innovation as well as the subsidies and taxation from the government through policies. This step is very important that would influence the change in resource use patterns.

4) Learn and Evaluate: From the technology innovation and policies designs in the previous step, the analysis to investigate which technology innovation or policy is effective or ineffective and lesson learned could further use for the improvement in next iterative sequence.

In the following subsections, I am going to conclude this dissertation by analyzing the existing use of MFA indicators in sustainable resource use policies and then by proposing the potential use to developing countries with the case study for Lao PDR.

8.4.1 Examples of utilization of MFA indicators for sustainable policy is Japan and China

There are several examples for target setting of the indicators for sustainable resource use policy. In Japan, the resource productivity, cyclical use rate, and final disposal amount are three main headline indicators of Sound Material Cycle Society Policy (Takiguchi and Takemoto 2008). All these three headline indicators are set and revised every five years. The target of resource productivity of Japanese's economy was set at 490,000 JPY (approximately 4,312 USD based on exchange rate of 1 JPY = 0.0088 USD) per tonne of resource use for FY 2025, which required Japan to increase their resource productivity by more than 100% within 25 years (averagely 2.9% per annum) compared to the base year 2000 (see details for target setting in Annex 4).

In emerging developing country, MFA indicators are now providing the evidence base information for sustainable resource management in the Circular Economy Promotion Law of China (Mathews and Tan 2016). Based on the MFA framework, total of 17 indicators are now used in the Circular Economy Promotion Law of China. Resource productivity and the recycling rate are selected as two headline indicators. In 12th Five-Year Plan for National Economic and Social Development, China aimed at increasing their resource productivity by 15% between 2011 and 2015. The evaluation of the headline indicators shows that the targets could be achieved. The resource productivity increased from 5,382 CNY (approximately 775 USD based on exchange rate of 1CNY = 0.144 USD) per tonne in 2011 to 6,822 CNY (approximately 982 USD) per tonne (Hu et al. 2018), that was 26.7% increase during the observed period, indicating the target set for resource productivity in the 12th Five-Year Plan for National Economic and Social Development could be successfully achieved.

8.4.2 Recommendation for utilization of EW-MFA results for sustainable resource management policy design in developing country, a case study for Lao PDR

Based on the experiences from the above examples, to implement the MFA indicators as the headline indicators for sustainable resource management policy in other developing country, the results from the comprehensive EW-MFA and Resource Efficiency Analysis of Lao PDR would be used for drafting the headline indicators for sustainable resource development for Lao PDR.

Three scenarios are developed to represent the future trends of three headline indicators including DMC, DPO, and resource productivity. The annual growth rate of GDP proposed by the Government of Lao PDR in the latest Five-Years National Socio-Economic Development Plan (2016-2020) is used (Ministry of Planning and Investment of Lao PDR 2016) to estimate the future GDP from 2016 to 2025. Using estimated GDP and projected DMC, the resource productivity could be roughly estimated. The details explanation for assumptions in each scenario are given in Annex 5.

From scenario development, the results show that in all scenarios, DMC will continuously increase. As proposed in Business-As-Usual (BAU) scenario, DPO will be more than doubled in 2025, increase from 40.9 million tonnes to 98.7 million tonnes. In Scenario 1, with growth rate of DMC as 12% per annum (annual growth rate between 1988 and 2015 was 9.3%), DPO was offset by reducing the emission intensity. If the consumption and outflows patterns are to follow the assumption made for this scenario, even with higher resource consumption, this would help to reduce the DPO to 90.8 million tonnes (about 8% reduction compared to BAU scenario). In the resource efficiency scenario (Scenario 2), by decelerating the growth rate of resource consumption (from 9.3% to 6% per annum), this could help to bring emissions outflows down to 52.3 million tonnes (almost 50% reduction compared to BAS scenario).

In terms of resource productivity, If the country aims to catch-up to the resource consumption per capita of other industrial countries, with the projection of GDP based on the aspirations expressed in the government development plan, this would decrease the resource productivity to level of 31.4 USD per tonne of resource use. The increasing of resource efficiency could be identified only in the scenario 2 (resource efficiency scenario). In order to achieve the improvement of resource productivity, slow down the growth rate of DMC (Scenario 2) could help to improve the resource productivity by approximately 14% within 2016 to 2025. Based on concept of the consumption and accumulation pattern proposed by Bleischwitz et al. (2018), the DMC would continuously increase for developing countries, especially when there are in the "growth stage". Based on Bleischwitz et al. (2018)'s results, certain threshold for saturation of DMC happens when GDP (expressed in PPP: Purchasing Power Parity) reached 12,000 USD per capita for steel and cement, and at 20,000 USD per capita for copper. Based on this theory, the results from this study clearly show that Lao PDR is still in the very beginning of the "growth stage" (see details for consumption and accumulation stage in Annex 6). Thus, immediate decreasing growth rate of resource consumption would not happen very soon for Lao PDR but slower the growth rate of resource consumption could be considered as the achievable target with innovative system-wide policy design.

If the scenario 2 is to be selected as the ideal scenario for setting the target for sustainable resource use policy in Lao PDR, the further investigations to set the specific targets in order to achieve the increasing of 14% of resource productivity and limit the growth rate of DPO at 3% per annum, would be definitely required. Comparing these target setting to the successful example discussed above, effectively implementations of the technology innovation from public and private sectors, and policy support by subsidies and taxes from the government, accompanied by learning and evaluating process, the sustainable resource management policy for sustainable development in Lao PDR could be framed by transforming the knowledge gained from this dissertation into the real-world public policy design.

CHAPTER 9
Summary of publications and conferences from this dissertation

1) Xaysackda Vilaysouk, Shinsuke Murakami: Material flow analysis for sustainable resource use in Lao PDR: the potentials and challenges. the International Society for Industrial Ecology (ISIE) 12th Socio-Economic Metabolism section conference and 5th Asia-Pacific conference, Nagoya University, Nagoya, Japan; 09/2016
2) Xaysackda Vilaysouk, Shinsuke Murakami, Heinz Schandl: Assessing a Physical Dimension of Lao Economy through Material Flow Analysis. The 9th biennial conference of the International Society for Industrial Ecology (ISIE) and the 25th annual conference of the International Symposium on Sustainable Systems and Technology (ISSST), Chicago, USA; 07/2017
3) Xaysackda Vilaysouk, Heinz Schandl, Shinsuke Murakami: Improving the knowledge base on material flow analysis for Asian developing countries: A case study of Lao PDR. Resources Conservation and Recycling 12/2017; 127:179-189., DOI:10.1016/j.resconrec.2017.09.006
4) Xaysackda Vilaysouk, Shinsuke Murakami, Heinz Schandl : The Industrial Ecology Knowledge to support Sustainable Development Goals in ASEAN: Opportunities and challenges. the Gordon Research Conference on Industrial Ecology, Les Diablerets, Switzerland; 05/2018
5) Xaysackda Vilaysouk, Heinz Schandl, Shinsuke Murakami: A comprehensive material flow account for Lao PDR to inform environmental and sustainability policy. Journal of Industrial Ecology (Online), DOI: /doi.org/10.1111/jiec.12764
6) Xaysackda Vilaysouk, Kamrul Islam, James West, Heinz Schandl, Shinsuke Murakami: Environmental impacts of Open-pit Copper mining in Lao PDR: A Life Cycle Assessment, the EcoBalance 2018, Tokyo, Japan; 10/2018
7) Xaysackda Vilaysouk, Shinsuke Murakami: Evolution of Industrial Ecology Research in ASEAN countries: A systematic literature reviews through bibliometric analysis, text mining and social network analysis approaches. (preparing to be submitted)
8) Xaysackda Vilaysouk, Alessio Miatto, Heinz Schandl, Shinsuke Murakami: Sociometabolic regime transition based on dynamic MFA in developing country. (in preparation)

Remark:

This dissertation is emended based on the published articles "Vilaysouk, X., H. Schandl, and S. Murakami. 2017. *Improving the knowledge base on material flow analysis for Asian developing countries: A case study of Lao PDR*. Resources, Conservation and Recycling 127: 179-189." and "Vilaysouk, X., H. Schandl, and S. Murakami. 2018. *A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy*. Journal of Industrial

Ecology Online First.”. Some parts of this dissertation is scheduled to be submitted to journals.

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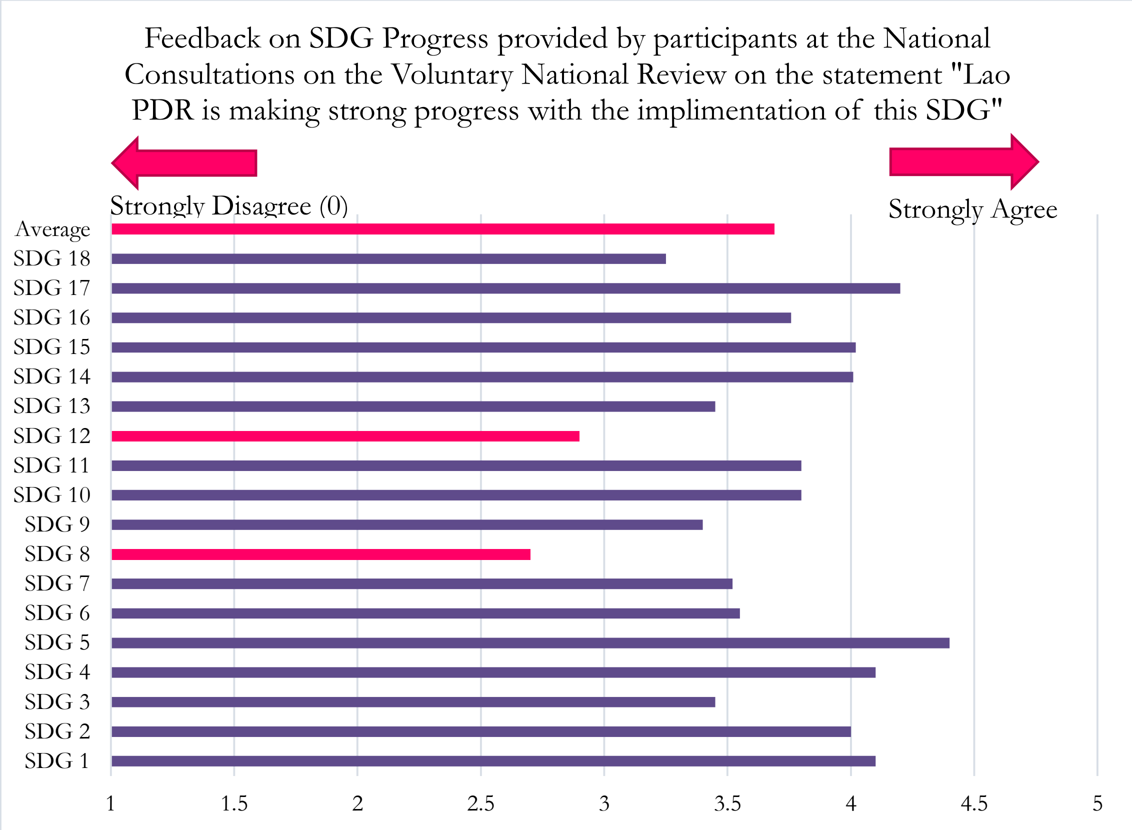
Annex 1: Stakeholder's perception of the progress of Lao PDR toward SDGs



Source: Adapted from The Government of the Lao People's Democratic Republic (2018)

Figure A1-1 Stakeholder's perception of the progress of Lao PDR toward SDGs

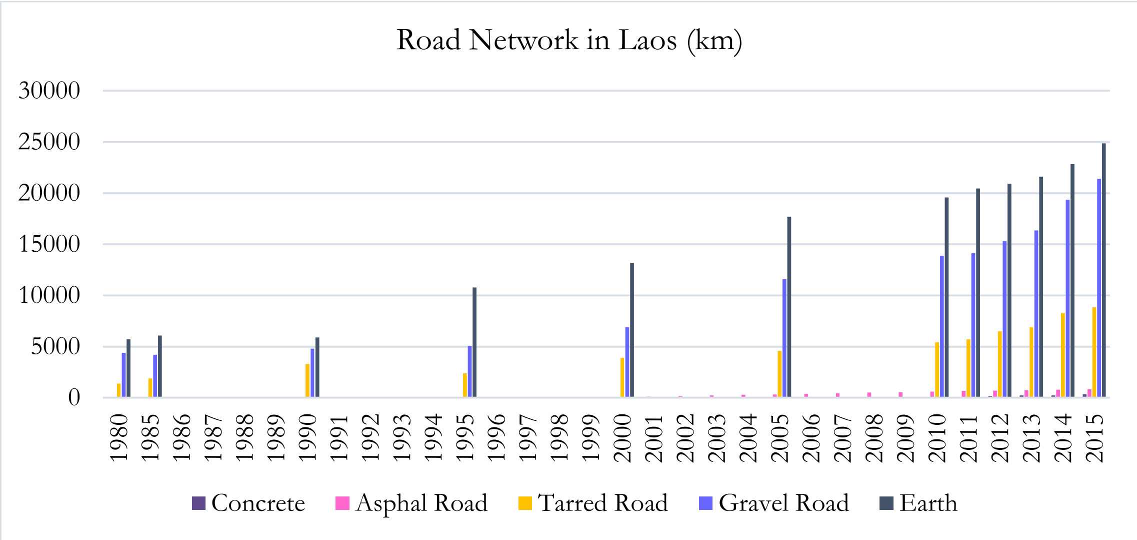
Annex 2: The assumption of lifetime distribution for dynamic MFA

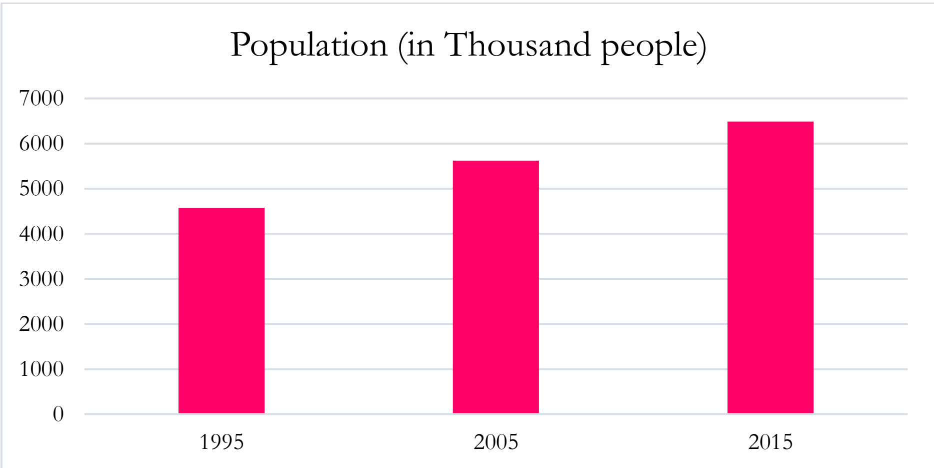
Materials	Decay parameters	Lifetime	Log-Normal distribution parameters	
Crop Residues	Median	4	mu (location)	1.386294361
	Standard deviation	1	sigma (scale)	0.239460047
Wood furniture	Median	8	mu (location)	2.079441542
	Standard deviation	2	sigma (scale)	0.182852406
Wood construction	Median	50	mu (location)	3.912023005
	Standard deviation	15	sigma (scale)	0.282529394
Natural gas	Median	2	mu (location)	0.693147181
	Standard deviation	1	sigma (scale)	0.433850673
Petroleum	Median	3	mu (location)	1.098612289
	Standard deviation	3	sigma (scale)	0.693694331
Ferrous slag	Median	1	mu (location)	0
	Standard deviation	1	sigma (scale)	0.693694331
Iron	Median	12	mu (location)	2.48490665
	Standard deviation	8	sigma (scale)	0.536360021
Non-ferrous slag	Median	1	mu (location)	0

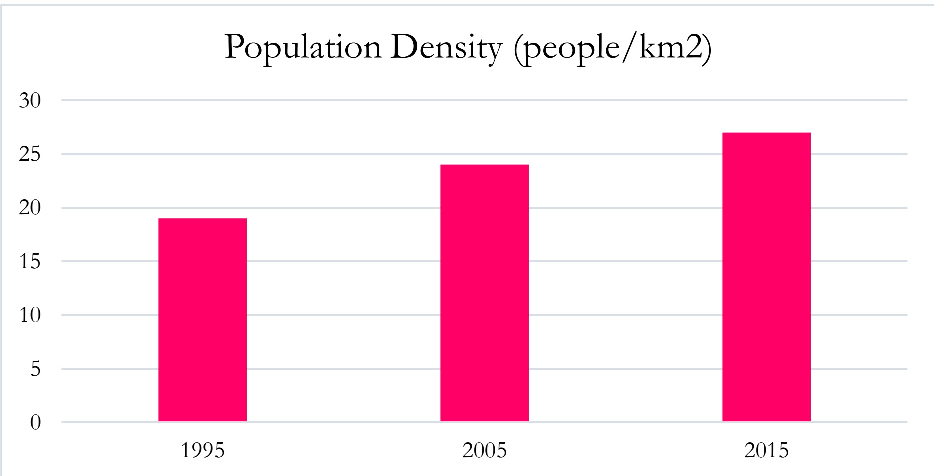
	Standard deviation	1	sigma (scale)	0.693694331
Other metals	Median	5	mu (location)	1.609437912
	Standard deviation	8	sigma (scale)	0.881832579
Non-metallic minerals - construction dominant	Median	35	mu (location)	3.555348061
	Standard deviation	10	sigma (scale)	0.270434462
Non-metallic minerals - industrial or agricultural dominant	Median	5	mu (location)	1.609437912
	Standard deviation	2	sigma (scale)	0.362356566

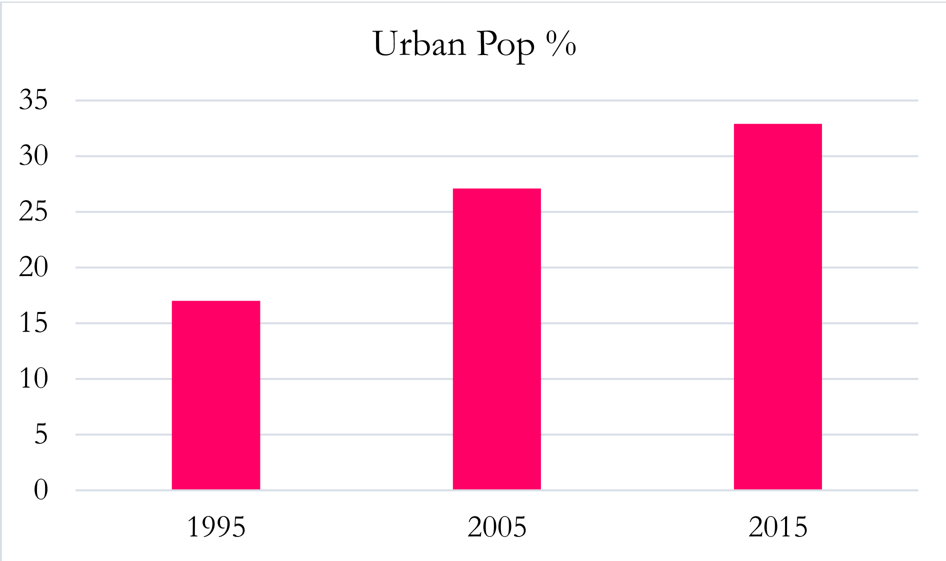
Annex 3: Some socioeconomic parameters related to infrastructure development and housing in Lao PDR

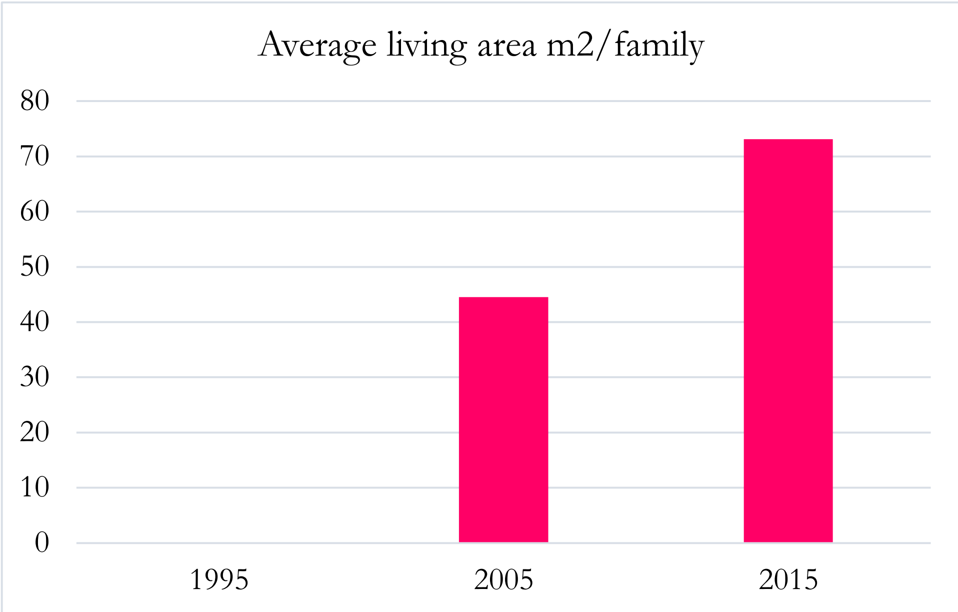
Note: Data from (Lao Statistics Bureau 2015b, 2005, 2015a) illustrated by author

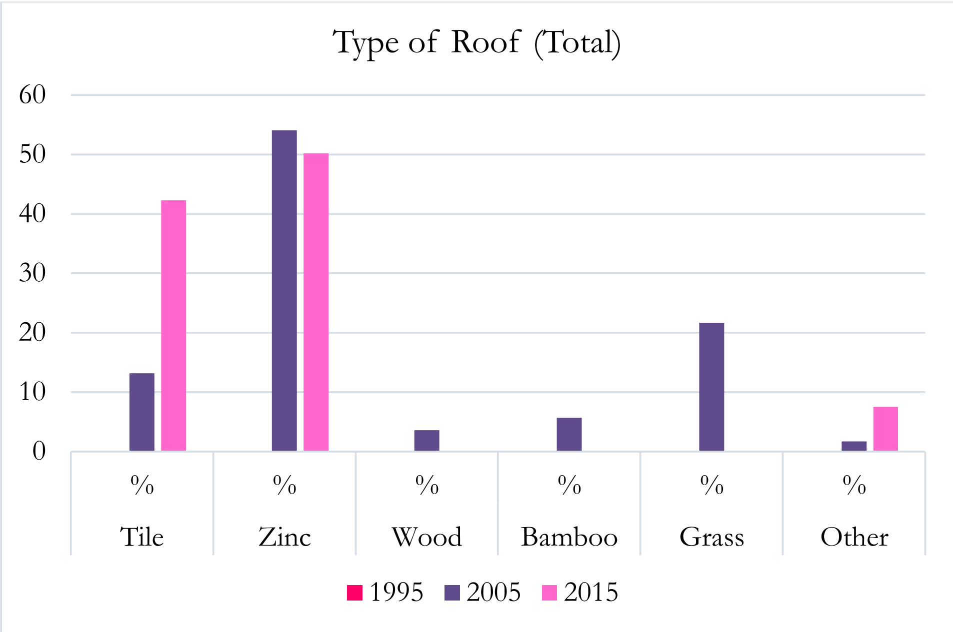


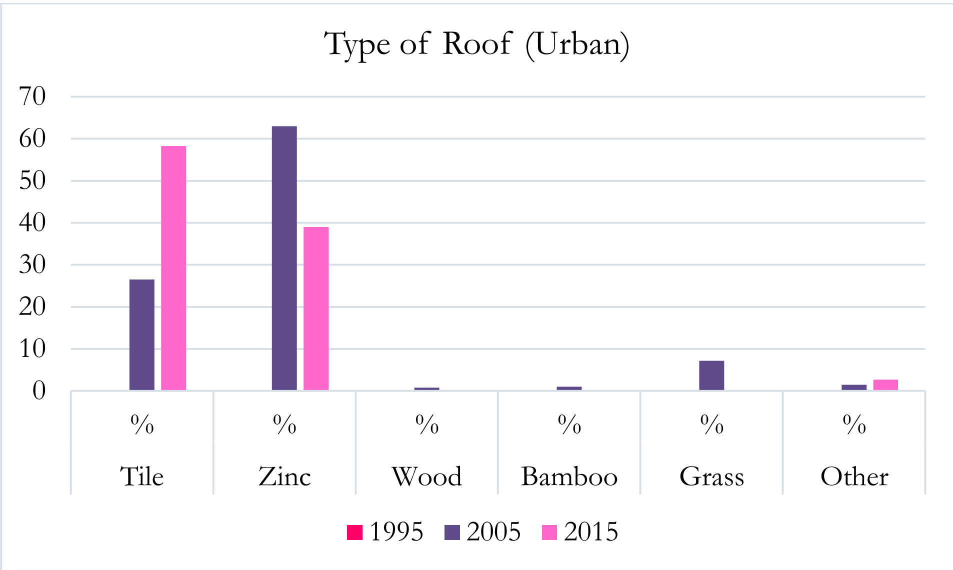


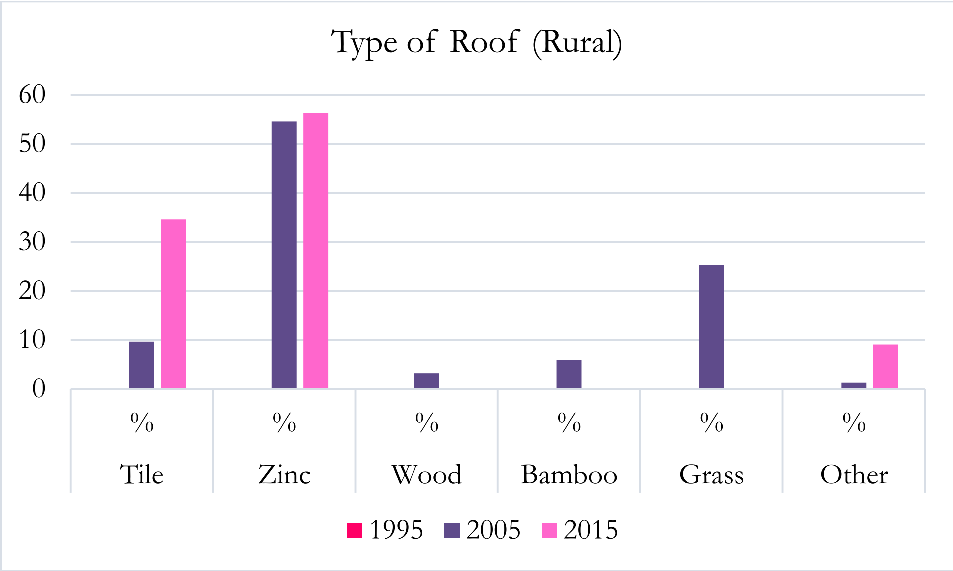



Urban Pop %
35
30
25
20
15
10
5
0
1995
2005
2015

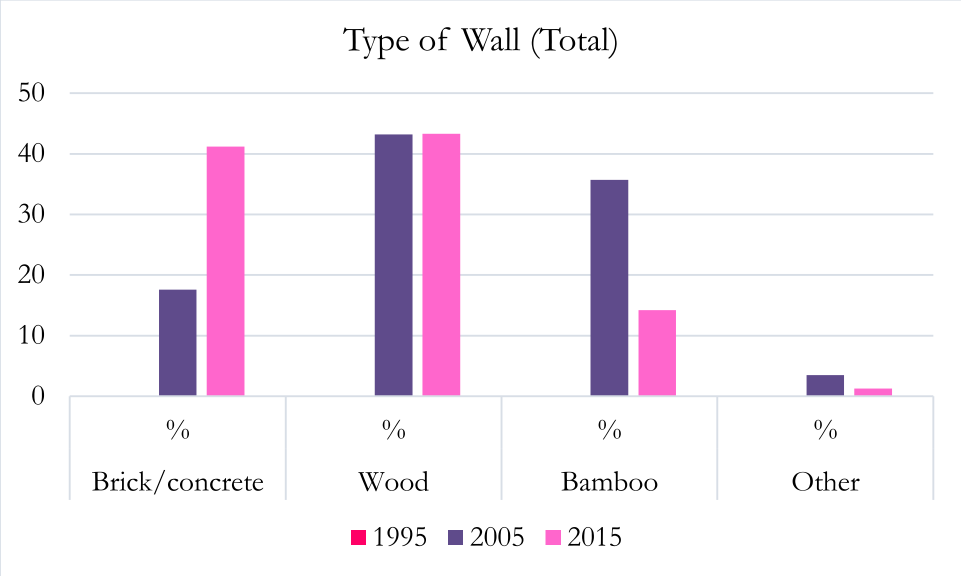

Average living area m2/family
80
70
60
50
40
30
20
10
0
1995
2005
2015

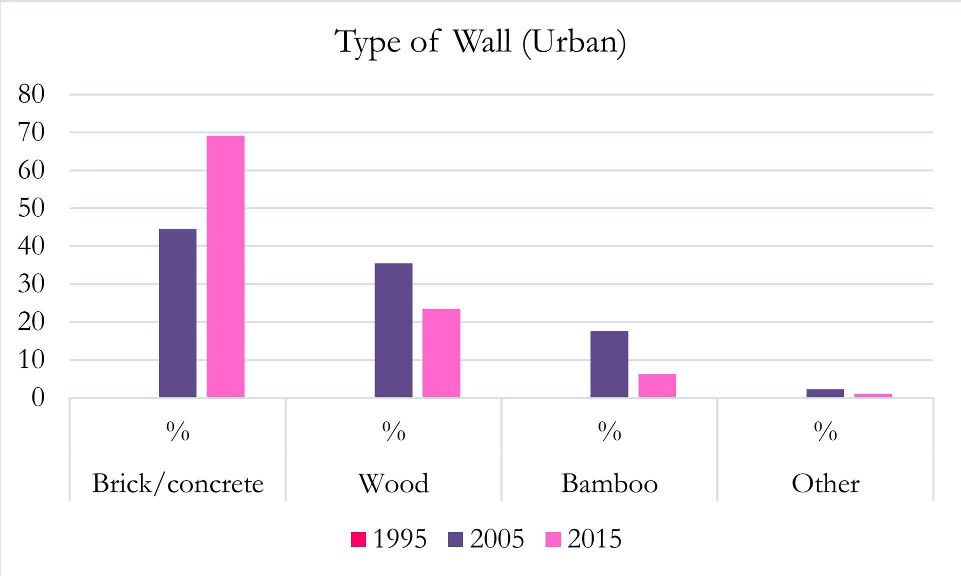

Type of Roof (Total)
60
50
40
30
20
10
0
%
Tile
Zinc
Wood
Bamboo
Grass
Other
1995
2005
2015

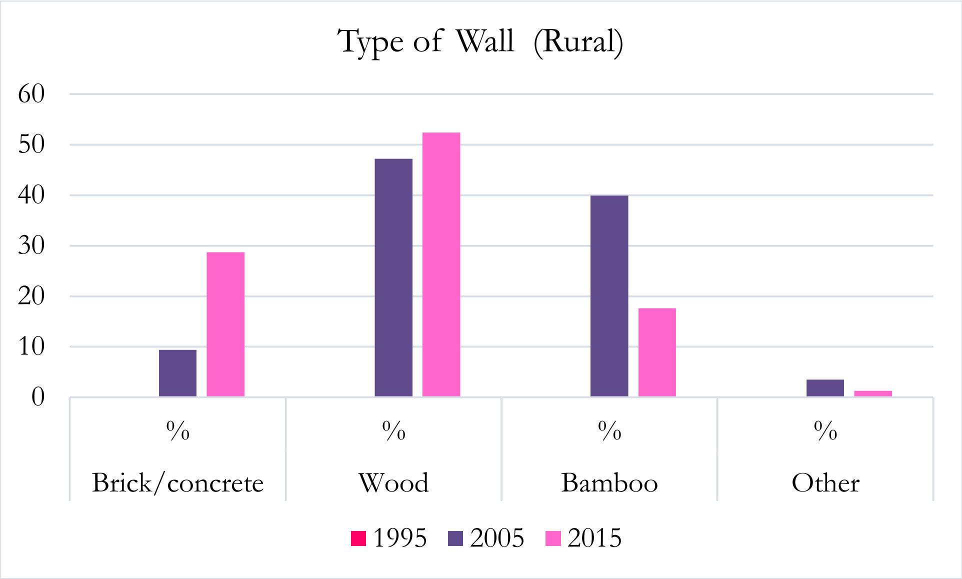

Type of Roof (Urban)
70
60
50
40
30
20
10
0
%
Tile
Zinc
Wood
Bamboo
Grass
Other
1995
2005
2015

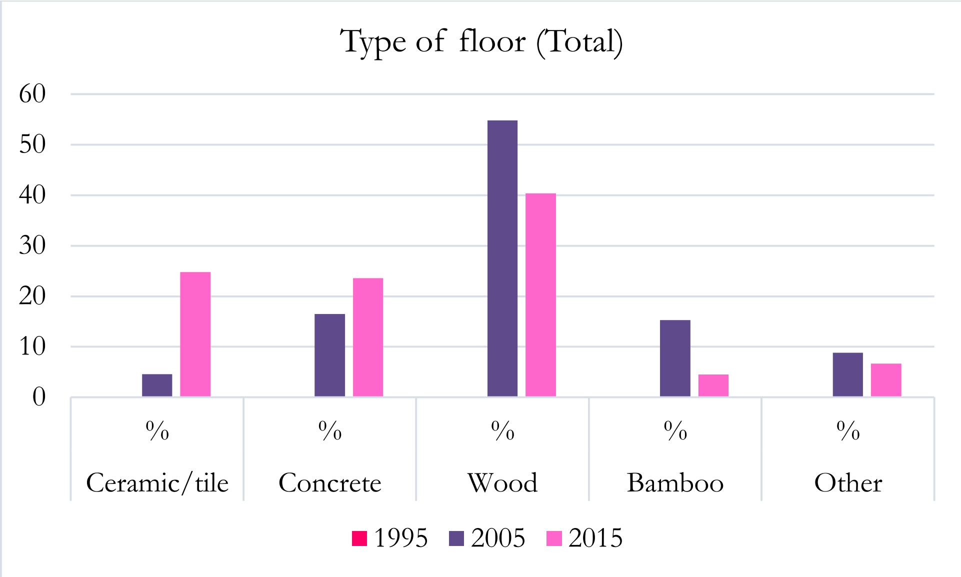


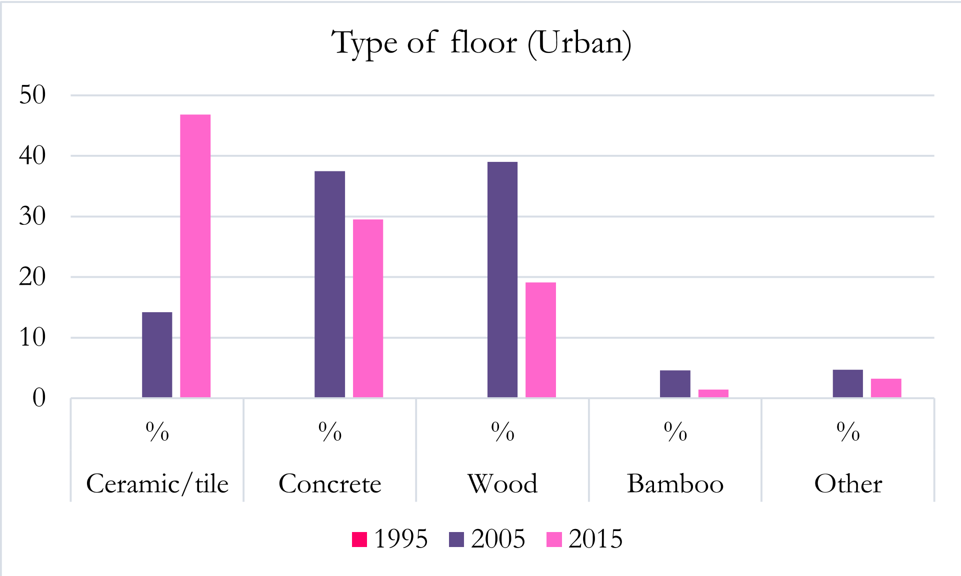
Type of Roof (Rural)
60
50
40
30
20
10
0
%
Tile
%
Zinc
%
Wood
%
Bamboo
%
Grass
%
Other
1995
2005
2015

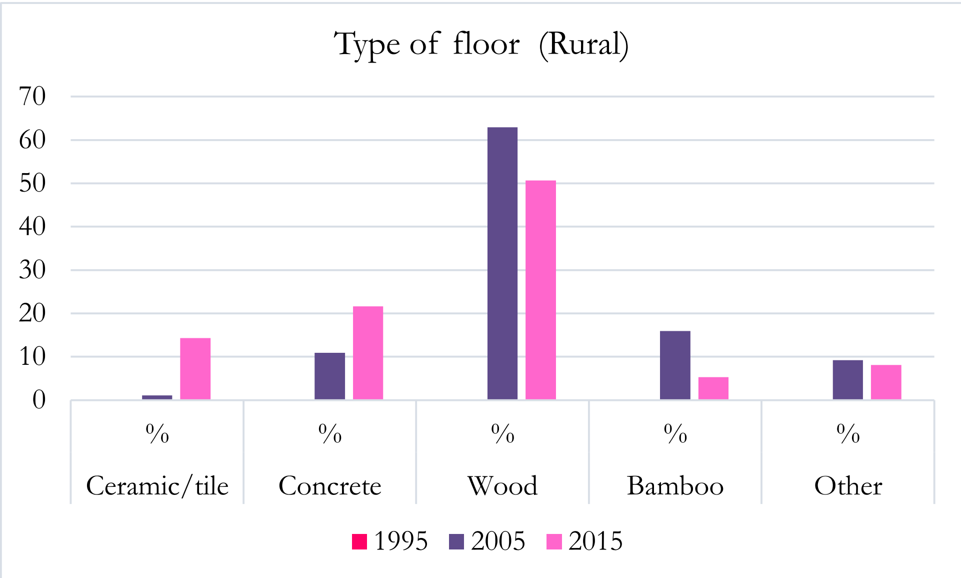

Type of Wall (Total)
50
40
30
20
10
0
%
Brick/concrete
%
Wood
%
Bamboo
%
Other
1995
2005
2015


Type of Wall (Urban)
80
70
60
50
40
30
20
10
0
%
Brick/concrete
%
Wood
%
Bamboo
%
Other
1995
2005
2015

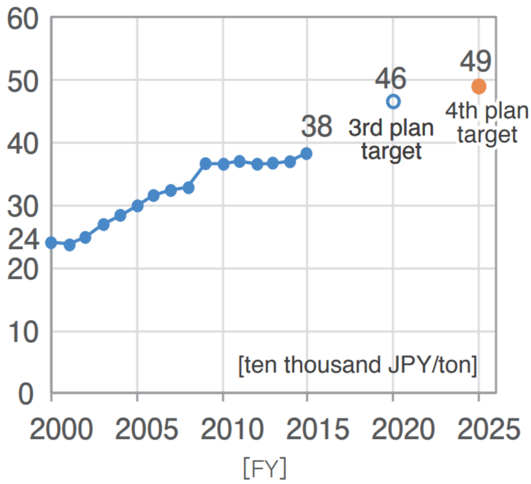

Type of Wall (Rural)
60
50
40
30
20
10
0
%
Brick/concrete
%
Wood
%
Bamboo
%
Other
1995
2005
2015


Type of floor (Total)
60
50
40
30
20
10
0
%
Ceramic/tile
%
Concrete
%
Wood
%
Bamboo
%
Other
1995
2005
2015

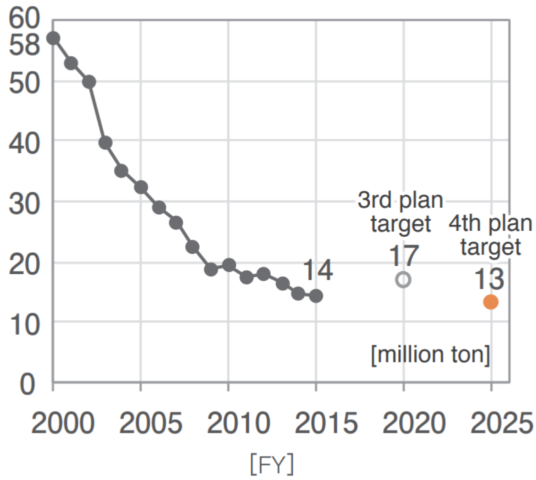

Type of floor (Urban)
50
40
30
20
10
0
%
Ceramic/tile
%
Concrete
%
Wood
%
Bamboo
%
Other
1995
2005
2015


Type of floor (Rural)
70
60
50
40
30
20
10
0
%
Ceramic/tile
%
Concrete
%
Wood
%
Bamboo
%
Other
1995
2005
2015

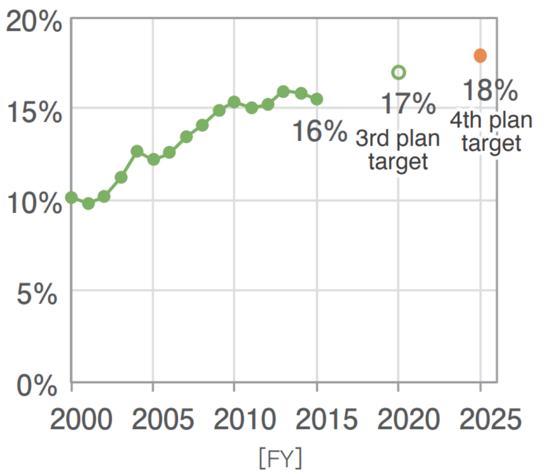
Annex 4: Sound Material Cycle Society Headline Indicators



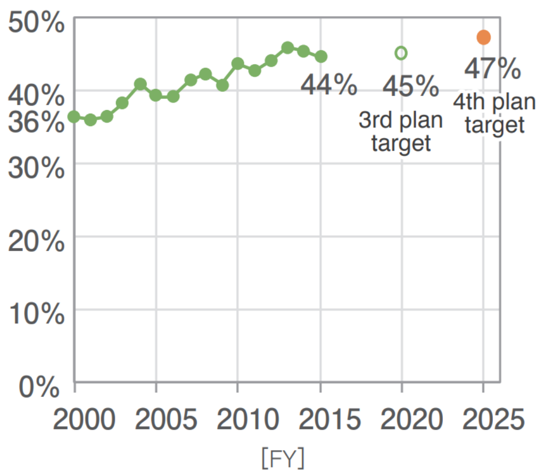
Resource productivity



Final disposal amount



Cyclical use rate (resource base)



Cyclical use rate (waste base)

Source: (Ministry of Environment of Japan 2018)

Annex 5: Scenarios development to inform policymakers on future DMC, DPO, and RP for 2016-2025

Business as usual scenario (BAU) assumed that DMC will increase based on the historical growth trends from 1988 to 2015 as 9.3% per year and the ratio of DPO per DMC assumed as the constant rate of 0.33.

Scenario 1 (catching-up scenario), assumed that DMC would grow faster than the historical rate aiming to catching-up with DMC per capita of other industrial countries with the annual growth rate of 12% during 2016 and 2025. The DPO is projected based the assumption of the DPO per DMC rate would decreased with annual rate of -3.25% (which for the case of Japan is -13.25% per year). Scenario 2 (resource efficiency), assumed that DMC would grow with a slower rate at 6% per annum. The DPO is projected with the same assumption made in Scenario 1. From these three scenarios, resource productivity was calculated from projected GDP divided by projected DMC.

The results for difference scenarios are shown in the figure below.

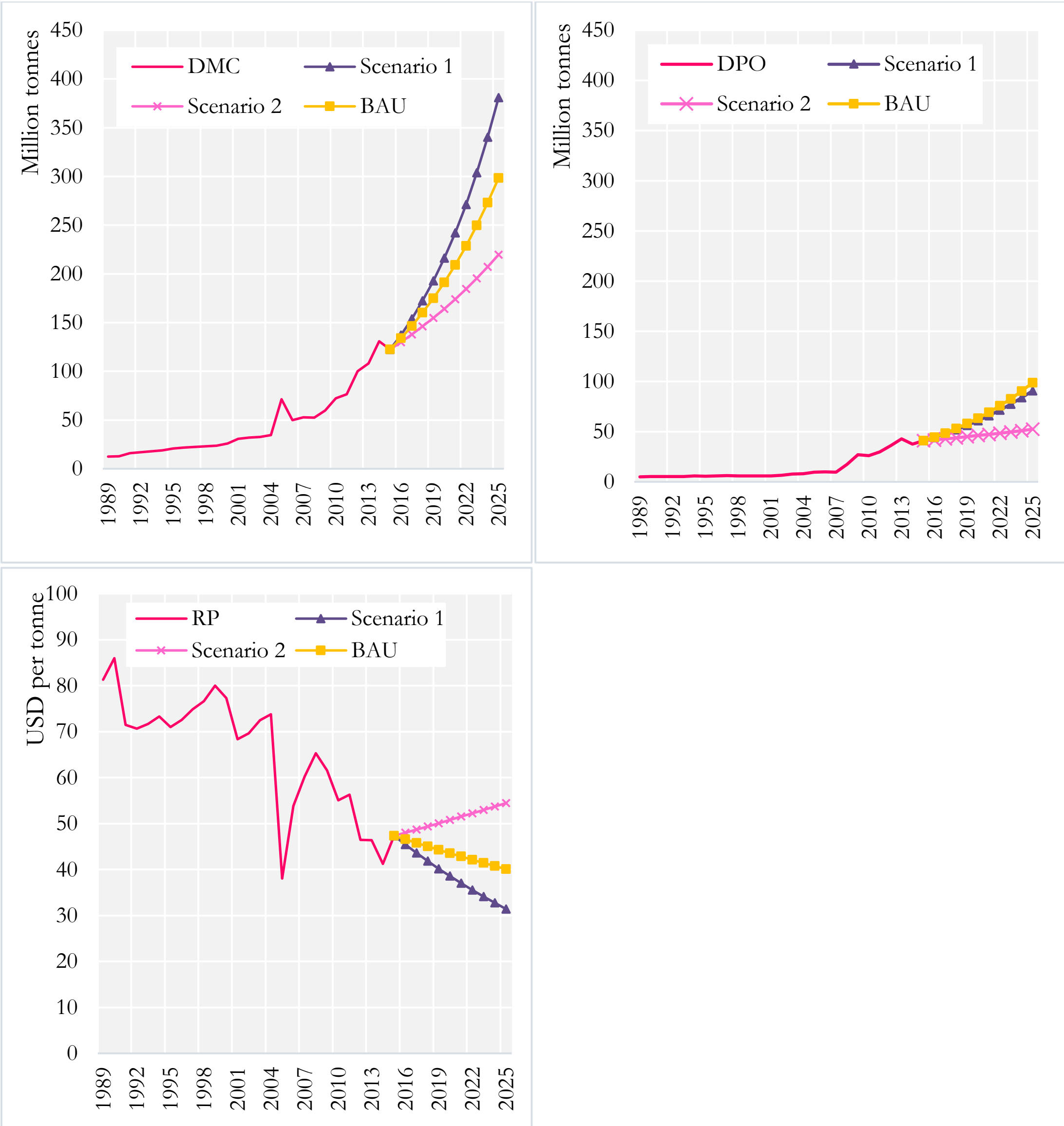
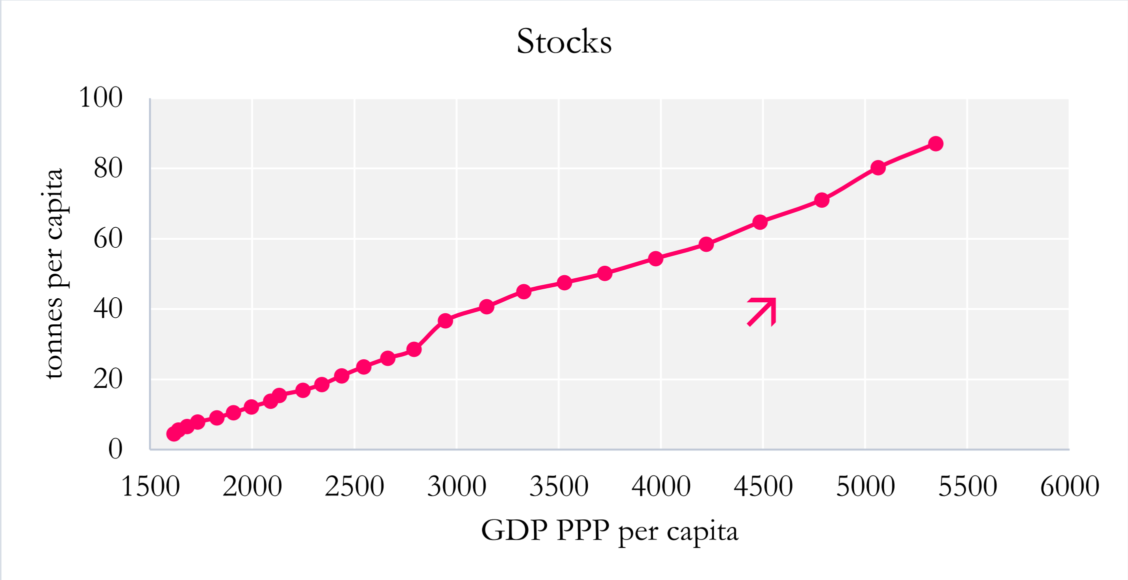


Figure A4-1. DMC, DPO, and resource productivity (RP) in Lao PDR from 1989 to 2015 and results from scenarios for 2016-2025

Annex 6: Development stage of Lao PDR's DMC and Stocks



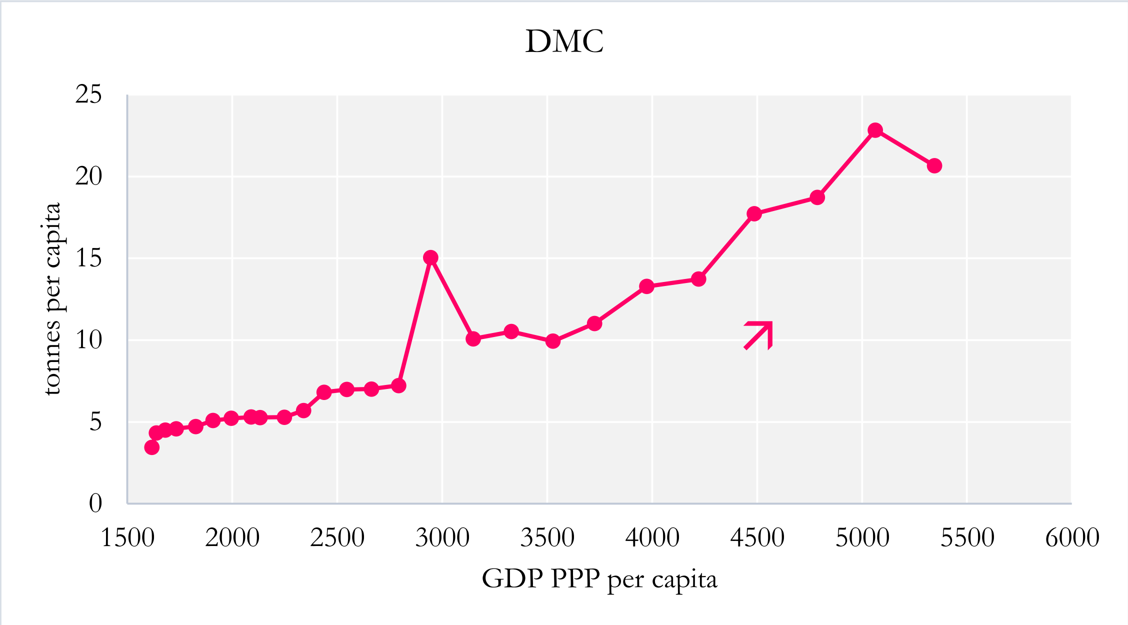


Table A6-1: Material Saturation Stages

Stage	DMC	Stocks	Description
Growth	↗	↗↗	Rapid accumulation of stocks
Maturating	→	↗	DMC saturate
Saturation	↘	→	Start of stocks saturation
	→	→	Steady stage
	↘	↘	Material efficiency adjustments

Source: amended from Bleischwitz et al. (2018)

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