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An information system for sustainable materials management with material flow accounting and waste input–output analysis

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ABSTRACT

Sustainable materials management focuses on the dynamics of materials in economic and environmental activities to optimize material use efficiency and reduce environmental impact. A preliminary web-based information system is thus developed to analyze the issues of resource consumption and waste generation, enabling countries to manage resources and wastes from a life cycle perspective. This pioneering system features a four-layer framework that integrates information on physical flows and economic activities with material flow accounting and waste input–output table analysis. Within this framework, several applications were developed for different waste and resource management stakeholders. The hierarchical and interactive dashboards allow convenient overview of economy-wide material accounts, waste streams, and secondary resource circulation. Furthermore, the system can trace material flows through associated production supply chain and consumption activities. Integrated with economic models; this system can predict the possible overloading on the current waste management facility capacities and provide decision support for designing strategies to approach resource sustainability. The limitations of current system are specified for directing further enhancement of functionalities.

1. Introduction

Sustainable materials management (SMM) has been advocated by the Organization for Economic Cooperation and Development (OECD) and US EPA [1,2]. The objective of SMM is to use materials in which their impacts on the environment are reduced throughout the material's life cycle. Without compromising social needs, the production and consumption activities in the economic system can be optimized for high resource efficiency [3]. The new SMM paradigm transcends traditional waste management systems, which have mainly focused on appropriate treatment and recycling methods. With a broader perspective, SMM approaches are based on a systematic understanding of the life cycle stages of the relevant materials. To implement SMM, decision makers require comprehensive information on the material flow systems. Therefore, material flow analysis (MFA) is considered an essential methodology for monitoring the resource use and developing environmental policy [1].

MFA provides a comprehensive perspective on resource use by illustrating the systems affecting complex material flow paths and flow rates through economic activities, providing a fundamental understanding that is critical for setting the priorities for SMM measures [4–7]. Among MFA methodologies, the economy-wide material flow accounts (EW-MFA) and environmentally extended input–output analysis (EEIOA) are the core methods used to measure a nation's material flows and productivity [8].

The EW-MFA method indicates the performance of an economy in terms of its resource consumption, efficiency, and material outputs using a system of material flow indicators, and waste outputs are also incorporated as material inputs in EW-MFA. EW-MFA analyses are often found in government or academic reports [9–12], which are generally read by only a few professional audiences. To raise public awareness of material flows, a few information systems

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have been made available online to report material flow indicators [13,14]. These information systems mainly store and share the data that have been calculated by the experts. However, inconsistencies arise among the indicators calculated over many years because the material items that are summed for each of the indicators often increase when more data become available from statistics derived using new survey methodologies. Updating the results of the indicators calculated by the old approaches is tedious and time-intensive. Therefore, it would be advantageous if the calculations and data collection could be accomplished in the information system because this would facilitate updating the data and maintaining the consistency of indicator outcomes.

Compared to EW-MFA, EEIOA is an industry-specific analysis tool. Several EEIOA models for MFA [15,16] were developed to analyze the material flow issues at the industry level. Used in conjunction with a yearly database, EEIOA can be a useful tool for diagnosing environmental issues associated with complex supply chains and guiding decision makers to develop more optimal protocols for certain production or consumption activities [17]. Because SMM involves the policies of different government agencies towards different materials, the efficacy of SMM requires collaboration among government agencies. Because most of these agencies are generally responsible for only the data pertaining to certain materials, the decision makers in each agency may fail to develop integrated SMM practices that consider all the opportunities available throughout the entire life cycles of associated materials. The life cycle perspective can also aide decision making in industries by elucidating the maximum economic value of the materials that can be attained through a variety of reduce, reuse, and recycle approaches.

The implementation EW-MFA and EEIOA requires intensive professional data management. Analysts must collect all relevant data from varied sources, such as the customs agency, agriculture department, energy agency, and many others. The collected data must be well organized to facilitate the extraction of valuable information. The relevant data management procedures include data cleaning, data organizing, and developing the connections among related datasets. Enormous effort can be saved by using computers and the internet to execute these tasks, which would further enable the processed information to be available to serve the unique demands of different users. Some previous researches addressed data storage [2,14,18–21]. The objective of the research presented in this paper is to integrate these MFA tools and the relevant databases in a way to provide widely accessible functionality for engaging wider SMM stakeholders. In addition, the automation of data collection can avoid the mistakes in manual data management possibly resulting from typos or ignorance in complicated data processing procedure.

Among the SMM related databases that have been developed in various countries, the European Union (EU) operates the most comprehensive one. The European database contains data on material production and waste management, and the MFA's function is also included, which can be used to determine national indicator trends. National indicators are also accessible in Japanese and Australian databases; however, data on the material sources and end processes are incomplete, and moreover, the MFA application is not available in either of these two databases. Nevertheless, Japan has developed Input–Output Tables (IOT) for Analysis of Environmental Fields [18]. The database established by the United States is insufficiently complete for practical purposes because data are collected only by voluntary submission from the manufacturers. The database developed in this study is similar to that used in Japan's project [18], which can reveal the relationships between domestic materials and economic activities. Compared to the currently developed databases, the database proposed in this study exhibits more comprehensive with detailed data on material production and waste management. In addition, several online MFA applications have been developed to provide national indicators and trends.

The purpose of this research is to present an evolving SMM information system that can illustrate the material flow system at both national and industrial levels. Based on an information system framework, SMM applications can be developed by accessing a database that is integrated with models of economic activities and material flows. The integration of EW-MFA and waste input–output (WIO) modeling is a key functionality of the proposed system. The following sections of this paper detail the development of the proposed information system, and the features of the developed applications are shown in the demonstration section.

2. SMM structure and function for serving diverse information

The development of this system aims at broadening the applicability of SMM information. The framework was designed to provide EW-MFAs and an IOT extended to include resource flows and waste streams. Furthermore, the framework empowers users to apply the system to develop other material management decision-making tools that will become necessary in the future. The framework as described below introduces the material flow data to the system, and the evidence derived from this framework provides insights for materials management. The hierarchical layers and features of the system are introduced in the following sections.

2.1. SMM structure: hierarchical layers from data to application

The framework developed to provide an infrastructure that can serve extensive data is drawn in Fig. 1. From data sourcing to application, the system is composed of a raw data layer, the resource data layer, the algorithm layer, and the application layer, with the data flowing from the bottom raw data layer to the top application layer.

The application layer delivers interactive charts and tables specific to different users' concerns. The tools incorporated in the application layer are classified into three types: the reporting of national indicator calculations, the analysis of material flows, and the simulation of a given specific scenario of material use. Governmental users can use the indicator reports to monitor trends in the resource management performance of a country. Some information components are directly filtered from the database, while others are processed and calculated by the models for the purposes of prediction, classification, or relationship mapping. All relevant analysis models are stored in the algorithm layer as the core of the application layer. The application layer incorporates two parts: the application systems and the user interface, which is customized to provide the relevant information for different stakeholders.

Automating the process of integrating the raw data layer with the models in the algorithm layer can save tedious work when surveying massive data quantities. Academic users can filter and download only those components of the raw data that are relevant to their particular applications. Information that provides insights into the material and waste flow situations can become more comprehensive as diverse applications are developed in the future. SMM practitioners in both government and industry can more quickly respond to existing and potential issues of resource circulation and waste management that are identified by the proposed information system.

The raw data layer can store all the original data from many different sources. Datasets can be collected from many government

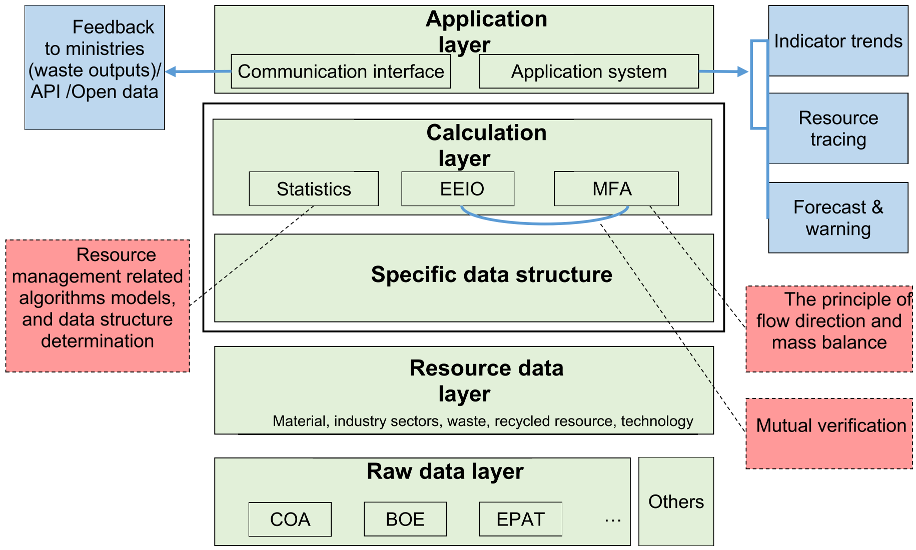

Fig. 1. Framework of the SMM system. The Raw data layers integrate the material flow and economic data from the Council of Agriculture (COA), the Bureau of Energy (BOE), and the Environmental Protection Administration of Taiwan (EPAT).

departments, such as statistical reports from the Council of Agriculture, energy balance tables from the Bureau of Energy, import/export data from the Customs Agency, statistics on non-metal minerals from the Bureau of Mines, IOTs from the Directorate General of Budget, Accounting, and Statistics, and industrial waste reporting data from the Environmental Protection Administration of Taiwan (EPAT).

The raw data layer is updated at least once every year. We expect this system capable of automatically retrieving data from all of sources. In this way, the maintenance of raw data can save labor and avoid manual mistakes in managing the imported data. Since 2013, the datasets maintained by the EPAT have been automatically imported into the raw data layer of the SMM system, through the Central Data eXchange dynamic data interchange interface Application Programming Interface (API). The rest of data are either imported through the open data API of Taiwan government or the reading and conversion of data containing documents, such as spreadsheet files or tables in statistics report files. The reading and data process on tables in documents is still labor-intensive. After finishing an upgrade of data importing function in 2016, the data of industrial production, sales and stock will be able to be imported from the Industrial Development Bureau in Taiwan for richer industrial level material flow data.

The raw data on materials from different data sources have various classifications and need to be reclassified to integrate the data from different sources into the resource data layer. Our datasets are organized in a relational database management system that facilitates the data integration and data processing based on structural query language (SQL). In the database that stores the raw data tables, the original classifications of the raw data are retained, and new fields are added for the reclassification. Each material is reclassified in the fields designating its material category, life cycle stage, and producing industry. The material categories are biomass, metal, nonmetallic mineral, or fossil fuel, based on the raw material forming the majority of its composition. The life cycle stages of materials include raw materials, manufactured products, and wastes that can be either disposed of or recycled. The producing industries are categorized into three sectors, which describe economies with 522, 166, and 68 goods and services sectors, corresponding to the Standard Industrial Classification of the Republic of China. In this way, the system can link physical flows to different economic activities.

For each life cycle stage, the material data are further classified. The raw materials are classified among 52 types of raw materials, which are taken from the EU's reporting tables for domestic extraction of raw materials [22]. The manufactured products and the imported raw materials are classified according to the Harmonized Commodity Description and Coding System, which is used by more than 200 countries and economies [23]. The four-code classification encompasses 1249 commodities in Taiwan's database. The industrial wastes are classified among 30 categories, such as biotic waste, plastic waste, sludge, etc. [24].

Several material datasets have two or more data sources. The fossil fuel data come from both the Bureau of Energy and the Bureau of Minerals. Any one material item appearing in two databases is matched together by adding the fields in a cross-table reference. Data on the industrial consumption of commodities are sourced from the Customs Agency and EPAT's industrial waste database. Depending on different surveying methodologies, each statistics has different level of representativeness.

2.2. SMM function: rendering sector-specific flows

After the EW-MFA data are applied to identify the major material inputs and outputs of an economy, users may be interested in which industries are associated with the resource inputs and waste outputs. Therefore, the proposed website offers a page that renders industry-wide information, including the resource inputs and waste outputs of the industries of interest to users. Users can view all of the industries that consume the selected resource and the industries that generate the selected waste. In addition, users can choose an industry to obtain an overview of the types and amounts of wastes generated by the industry. This information is served from a national resource input–output table (NRIOT).

The well-structured design of sector-based data in the NRIOT is derived from the WIO table developed by Nakamura and Kondo [15,25]. With the data structured in this manner, SMM system tools can be developed to model material flows in response to a variety of activities in the production and consumption sectors. As shown in Fig. 2, the NRIOT comprises six adjacent sub-tables. The datasets of each sub-table are described as follows:

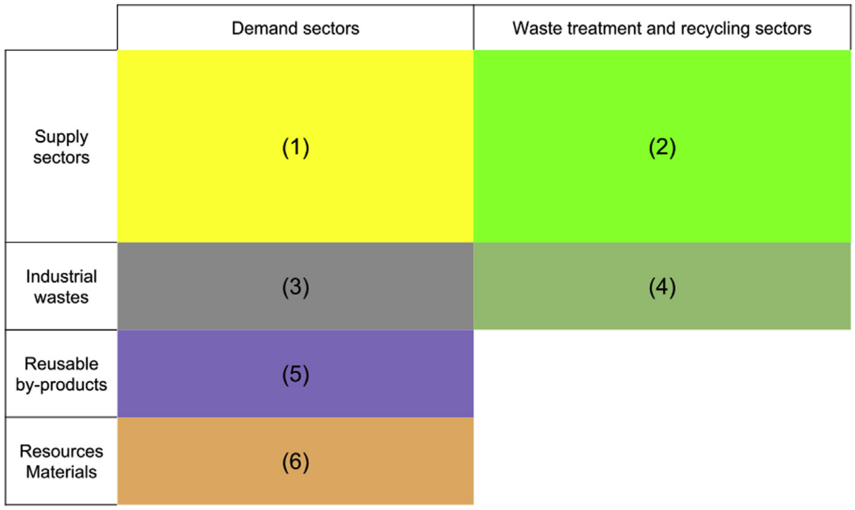

Fig. 2. Scheme of NRIOT, an assembly of inter-industrial monetary and material flow tables.

(1) Inter-industrial transactions between 68 goods and services sectors derived from Taiwan's benchmark IOT for 2011 [26];
(2) Consumption capacities of 31 end-of-life treatments of the wastes generated by 68 goods and services sectors;
(3) The amounts of 646 types of wastes generated by these 68 sectors;
(4) The amounts of 646 types of wastes treated by the 31 end-of-life treatments (listed in Table 1);
(5) The amounts of 646 types of industrial byproducts consumed by the 68 sectors; and
(6) Four material categories and 52 resources that are extracted or used by the 68 sectors.

2.3. Hardware and software

One web server and one database server are used to host the proposed SMM system. The two servers are accessed from and installed in the EPAT's data center. The adopted operating system is the Windows 2012 server, and the database server is established using Microsoft SQL server 2008. The web server software is Microsoft IIS 6.0, and the web application was compiled using various programming languages for web application, including ASP.NET, JavaScript, and HTML5. The core estimation tool for modeling industrial resource and waste streams behind the ASP.NET based web applications was built with C# programming language.

3. SMM function: monitoring economy-wide material flows

Our SMM information system can display several material flow indicators at the national level. Widely used EW-MFA indicators are included in this analysis to provide a comparison with the EU's member states. In accordance with the statistical methods of the EU, Table 2 lists the definitions of the indicators and the corresponding calculations. In addition to EW-MFA, national resource productivity (RP) performance can be observed to investigate the progress made in terms of resource efficiency, decoupled from economic development, from 2006 to 2014. RP is used by the OECD to measure how much GDP can be produced per unit domestic resource consumption. To measure the resource circulation performance, we incorporated Japan's 3R policy indicator into the system [27], in which the Cyclical Use Rate represents an indicator for the progress toward a Sound Material-Cycle Society.

Table 1
The end of life treatments with data in the database.

Categories	End of life treatments
Intermediate and final treatments	Landfill, ocean disposal, export, sterilization, chemical treatment, biological treatment, thermal treatment, incineration, physical treatment, solidification, stabilization, other treatments.
Reuses	Reuse as raw materials, reuse as additives, reuse as fuels, reuse as fodder, reuse as fertilizer, reuse as aggregate, reuse for soil amelioration, reuse for land reclamation, reuse as soil, other reuses.
Recovery as resources	Use of recovered resources, recover for raw materials, recover for materials, recover for fuels, recover for fodder, recover for fertilizer, recover for aggregate, recover for soil amelioration, other recoveries.

Table 2
Indicators of national level material flows [1,3,4,15].

Indicator	Full name	Calculation
IMP & EXP	Import and Export of Materials	Sum of the imported or exported goods for the four material categories based on major composition
DE	Domestic Extraction of Resources	Sum of the agricultural biomass production, and the fossil fuels, metal ores, and minerals extracted in Taiwan
DMI	Direct Material Input	$IMP + DE$
DMC	Domestic Material Consumption	$IMP + DE - EXP$
DPO	Domestic Processed Output	Sum of anthropogenic emissions to the air, water, and the waste for disposing of
DMO	Direct Material Output	$DPO + EXP$
RP	Resource Productivity	$GDP \div DMC$
CUR	Cyclical Use Rate	Fraction of recycled material and reused good to the DMI which includes the input of secondary materials

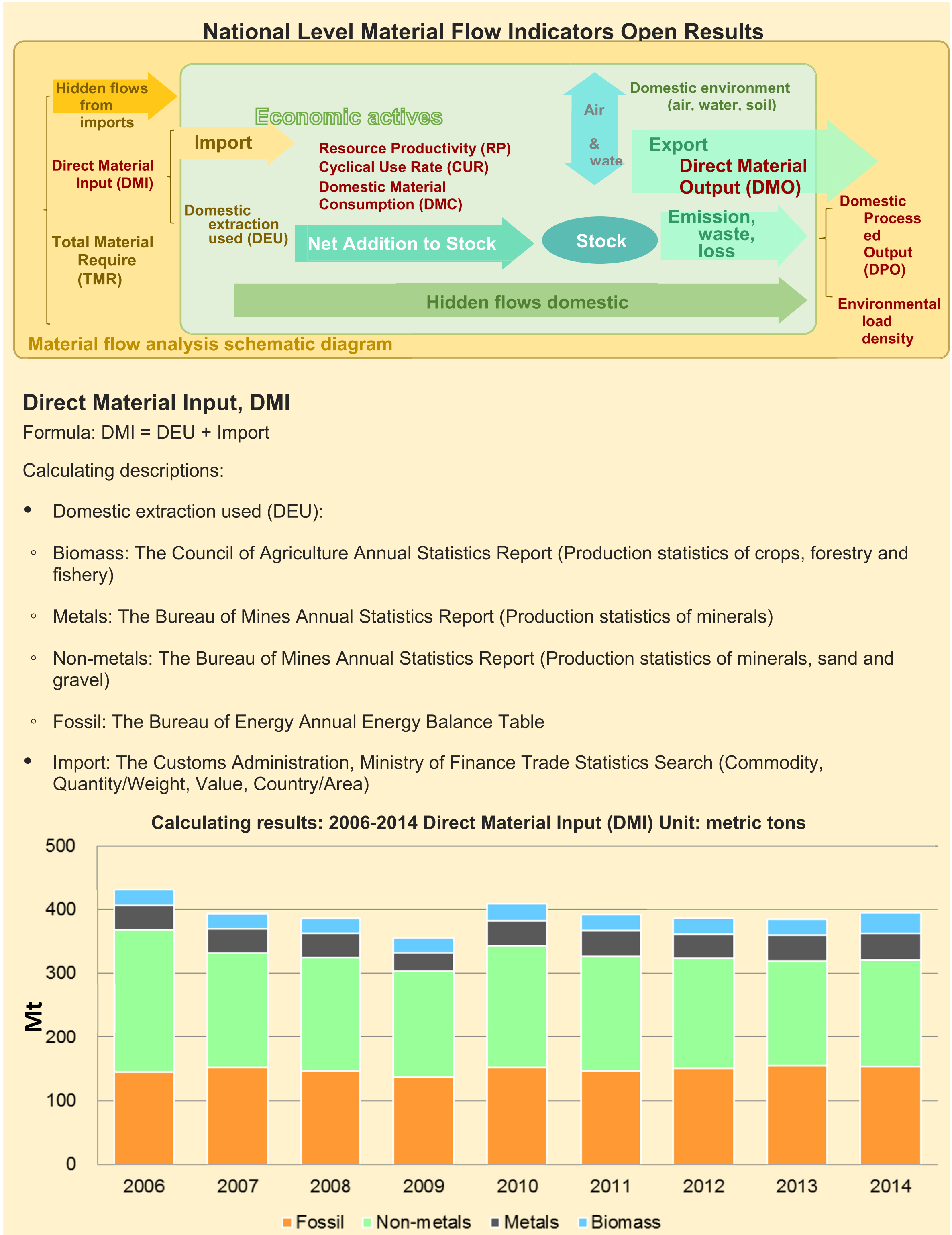

Fig. 3. DMI chart area in the EW-MFA indicators application.

Regarding the classification of materials, the materials are categorized as biomass, metal, non-metallic mineral, or fossil fuel. These material categories cover raw materials, manufactured parts or components, finished products, and discarded materials, which can be disposed of or recirculated in the economy. The table regarding the classification of commodities is provided in the Supplementary Material.

4. SMM application: modeling industrial resource and waste streams

SMM seeks efficient and environmentally friendly uses of resources through examining a material's entire life cycle stages, in which industries are consuming resources for manufacturing products and providing services. The novelty of this SMM information system is the integrated life cycle material flow model, which put together material inputs, product outputs, and waste output of 68 industries. In additional to national level aggregated indicators, the industrial level resources flows and waste stream data are stored in the database and organized to present material flow information for different stakeholders. At the end stage of a material's life cycle, material reuse and the waste prevention are of higher priority in SMM strategies. Therefore, the proposed system includes the reuse and recycling as the paths of waste streams from industries. The sector-based waste stream data are acquired from the EPAT's database of industrial waste and aggregated by sectors.

Using this SMM system, governments can identify the key industries by comparing which industries generate more wastes and which industries consume more resources. This information is placed in the sub-table (6) of the NRIOT shown in Fig. 2. The consumption of specific resources by different industries is available in our SMM system. In most countries, import and domestic extraction statistics do not specify which sectors consume how many resources, but the aggregated indicator and national scale. The material flow computation of the system employed an estimation method.

We estimated the consumption of resources for each sector by assuming the flow of resource commodities is proportional to the corresponding monetary flows from the sector producing resources to the sectors consuming the resource. The monetary information is available in national IOTs. Output coefficients derived from the IOT as Eq. (1) serve as the coefficients to allocate the national input of a given resource to all consuming sectors. In Eq. (1), each output coefficient *bij* is the fraction of the total output of sector i that is consumed by sector j. x_i is the monetary output of sector i, and $x_{i,j}$ is sector j's purchase on sector i's outputs. Assuming that the distributions of 1249 types of material inputs among the consuming sectors are proportional to the corresponding monetary flows into the 68 sectors, the consumption of each industry can be approximately calculated by Eqs. (2) and (3), where DE and IMP are the supply of the resource or material k from domestic extraction and import, respectively. The subscript i in equations refers to the sector supplying the resource or material k, and the subscript j indicates the one of the sectors as intermediate or final consuming industry of the resource or material k. The allocation of domestically extracted is based on the IOT for domestic goods and services; the allocation of imported resources is based on the IOTs for imported goods and services. The coefficients from domestic and imported IOTs are superscripted with *dom* and *imp*, respectively.

$$b_{i,j} = \frac{x_{i,j}}{x_i} \tag{1}$$

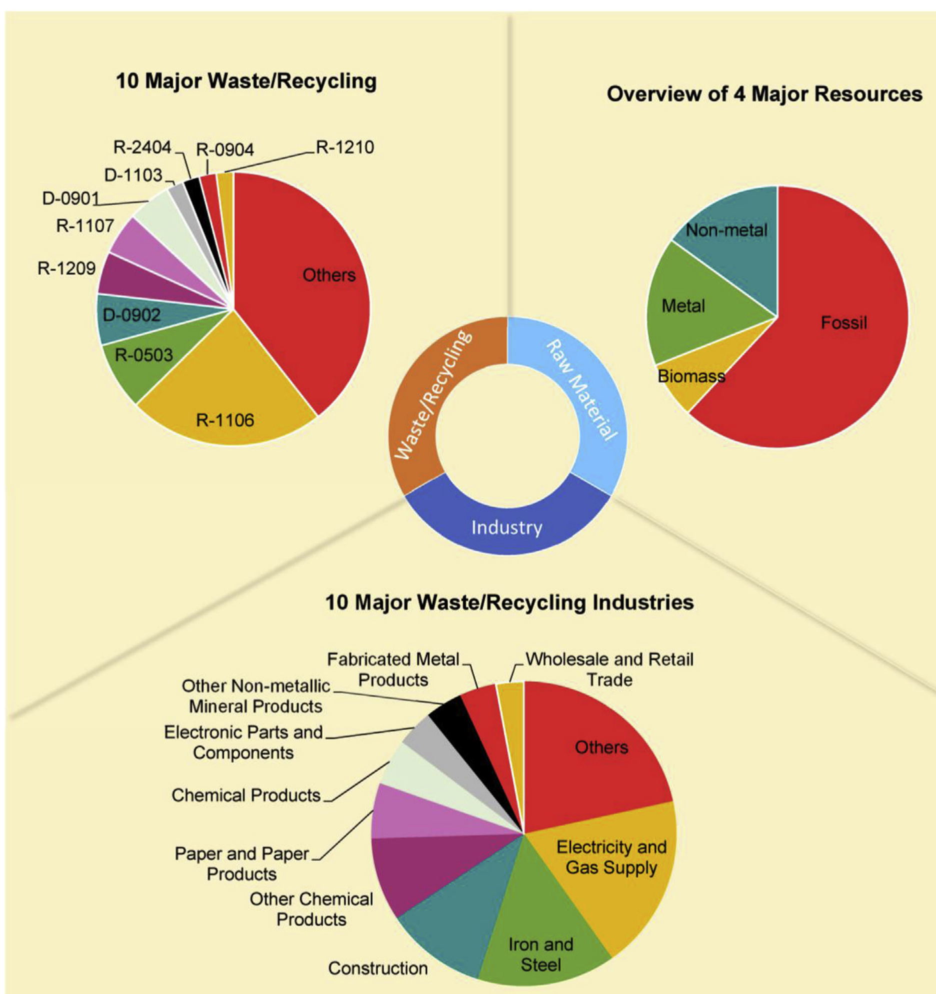

Fig. 4a. Gateway page into the three modules for refined data queries: raw materials, industrial materials, and waste materials.

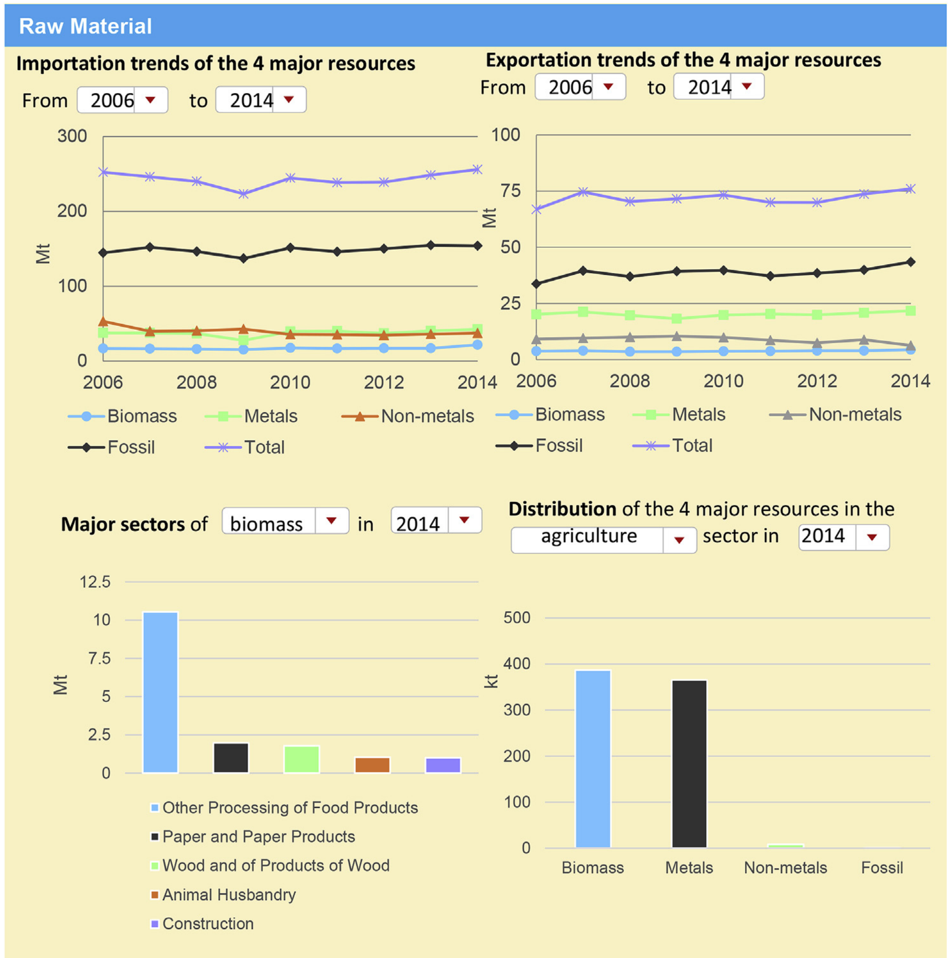

Fig. 4b. Data presented in the interactive raw material module.

$$DE_{i,j}^{k} = DE \times b_{i,j}^{dom} \tag{2}$$

$$IMP_{i,j}^{k} = IMP \times b_{i,j}^{imp} \tag{3}$$

For appropriate management of industrial wastes, the system can display the industries generating the waste of concern on bar charts that compare the differences among industries. In addition, the system can also support preventative waste management by indicating the downstream industries that purchase a good or service from the sector that generates the waste. New opportunities for waste reduction can be discovered and implemented by adjusting the economic structure. The production and export of certain products can indirectly cause pressure on waste generation.

Information regarding the driving forces of waste generation is based on the WIO, which models the linkages among sectors in complex supply chains [25,28]. Each sector's direct waste generation and indirect influence on the waste generation of upstream sectors k are calculated from Eq. (5) [15]. First, the Leontief inverse matrix derived from the IOT is multiplied by the array containing the specified demands across all sectors to obtain the outputs of all sectors that are caused by the specified demand Y. An array of waste generation intensities for all industries G is then multiplied by the calculated outputs across all sectors. The waste generation intensity G_k represents the generated amounts of waste k per unit production for all industries. In the matrix G_k, each coefficient $g_{i,k}$ is derived from Eq. (4). This information system compares the influences of different sectors on waste generation in pie charts. When users select a waste for analysis, the system performs the calculations for each sector by setting Y with zeros in all entries except the entry of the target sector, which is given the value of the final demand. A modeling result for coal ash is presented in Section 5.

$$g_{i,k} = \frac{W_{k,i}}{X_i} \tag{4}$$

$$W_k = G_k \times X = G_k \times (I - A)^{-1} \cdot Y \tag{5}$$

5. Applications of SMM system

This SMM information system has been online since 2014, currently accessible at http://smmdb.epa.gov.tw/smm/webpage/enter.aspx (presented in Chinese). This section describes the applications to SMM decision making. Then, the interface and part of the results of the web applications are demonstrated as shown in the following five figures. The applications comprise two parts: national indicator viewing and material flow tracing.

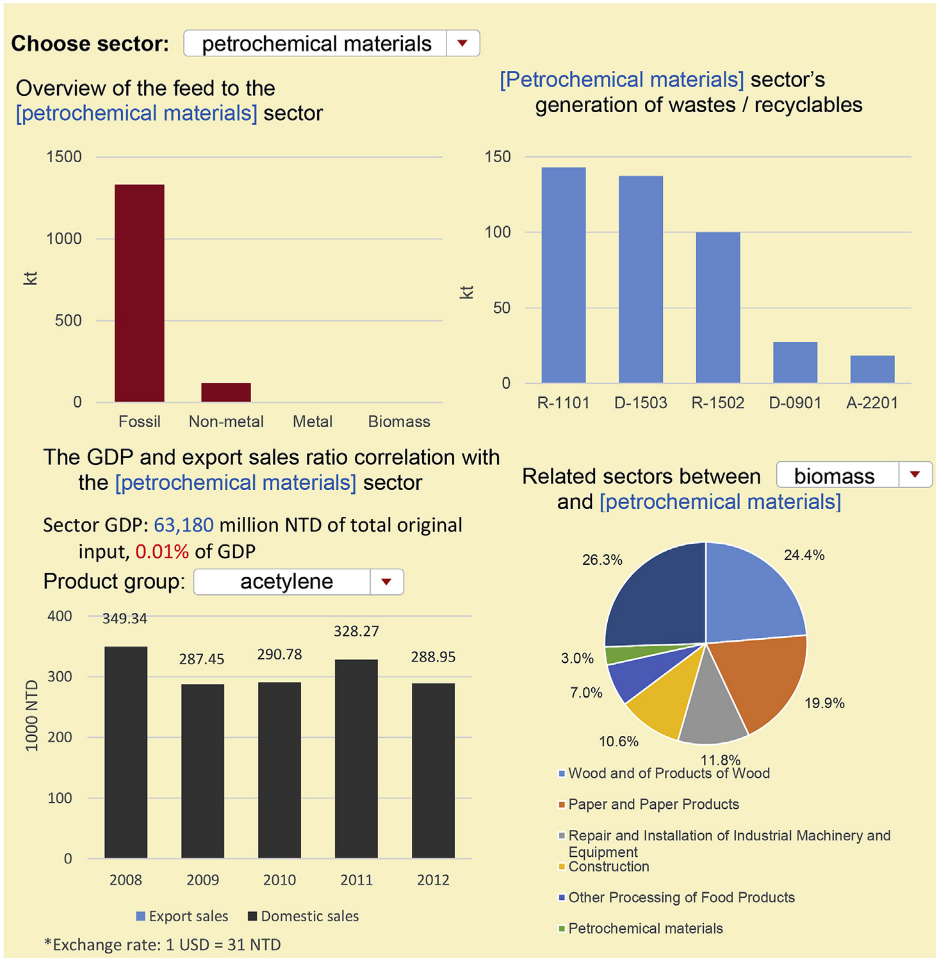

Fig. 4c. Data presented in the interactive industry module.

5.1. Applications in developing SMM measures

The national indicator application allows for monitoring the trends of the indicators mentioned in section 3 for biomass, metal, non-metallic mineral or fossil fuel. With such information, the policy analysis for SMM can examine whether or not the resource efficiency has been improving under the related policies. The formulation of practical SMM measures can also look into which commodities and which wastes dominate the overall material consumption and the overall output to the environment. The new measure or improvement on existing policy instrument can target at these commodities or wastes.

The analysis of the driving forces of waste may bring insights to waste prevention or the planning for waste management facilities. The information system can show which industries generate the most of a selected waste. Thus, the government can focus on supporting these industries in making bettering resource and waste management. In addition, when the decision makers identify the sectors of major driving forces on the selected waste, they may try to develop strategies to weaken the forces or ensure their waste management measures and facilities can afford the reuse, recycle, or treatment required to facing potential growth of waste generation.

5.2. Viewing national level material flows

Fig. 3 shows the webpage that displays the economy-wide material flow indicators, specifically for the Direct Material Input (DMI) indicator. The application can provide users with the data trends in material flow indicators from 2006 to 2014. These indicators include the DMI, Domestic Material Consumption (DMC), RP, Domestic Processed Output (DPO), Direct Material Output (DMO), Cyclical Use Rate (CUR), and environmental load density. For enhancing user experience, a diagram of the indicators system is shown at the top of the page. When a user clicks on the label of one indicator on the diagram, the page links to the interactive chart of the corresponding indicator. All of the indicators can be compared in bar charts or line charts. The indicator's different bar heights represent the stacking of the four materials: biomass, metals, nonmetallic minerals, and fossil fuel-based commodities.

Looking at the DMI trends of Taiwan, as shown in Fig. 3, the total DMI is decreasing from 431 to 394 Mt. The decoupling of GDP from the resource input can be observed on the line chart of RP (not shown in the figure). The stacked bar at the bottom of the figure highlights the fact that non-metallic minerals (in green) and fossil fuels (in orange) dominate more than 80% of the DMI. Therefore, the environmental impacts associated with the life cycles of non-

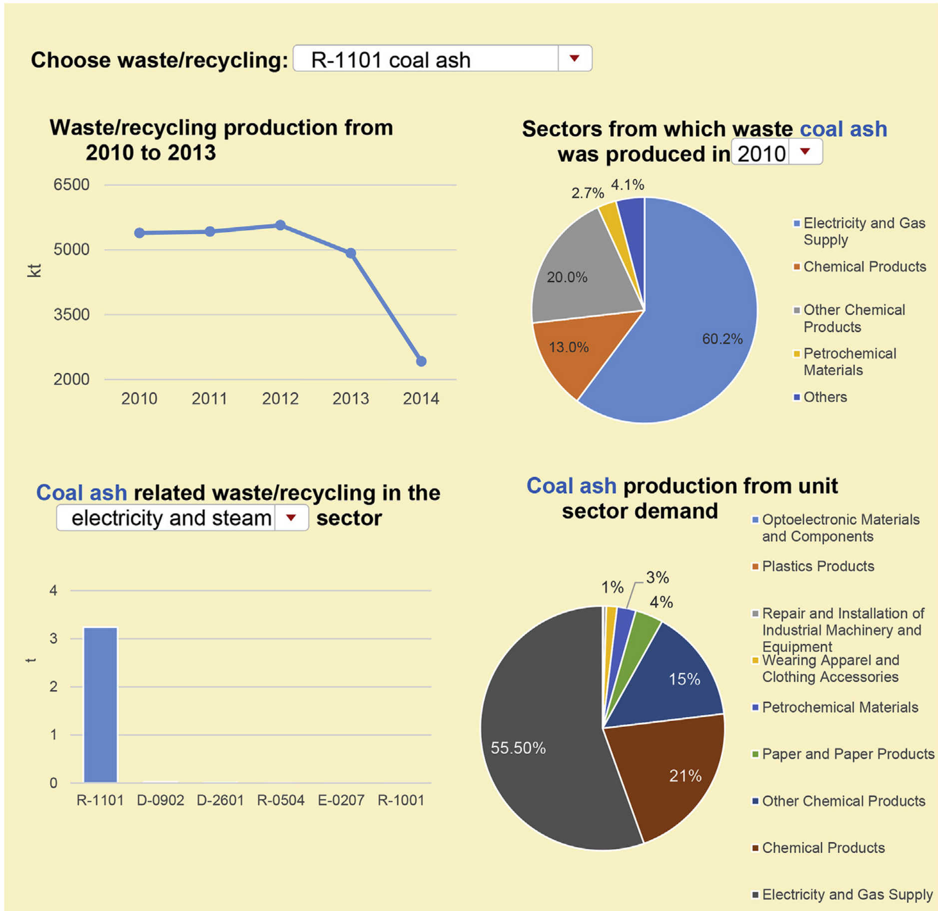

Fig. 4d. Data presented in the interactive waste/recycling module.

metallic minerals and fossil fuels are probably higher than the impacts of the other two materials, which add a minor contribution to the DMI. Similar to the DMI, the DMC subtracts exports from the DMI to exclude the material inputs that will be consumed by other countries. The fraction of fossil fuels in the DMC is higher than that in the DMI. The DPO reflects the environmental burden associated with the material output by summing the emissions to air and water resulting from the disposed wastes. Although the wastes have been significantly reduced in recent years, the growing CO_2 emissions dominate the DPO. SMM practices that can be implemented with respect to the sources of CO_2, including the use of fossil fuels and biomass materials, would be essential components of any comprehensive SMM plan. The transition toward an improved recirculation of resources in the economy can be monitored by the CUR indicator. The trend in this indicator shows that the CUR has almost doubled from 2006 to 2011 and may have reached a steady state or bottleneck to better resource circulation. New technologies and business models would be required to reduce Taiwan's demand for primary unused resources and improve waste treatment through resource circulation.

This application provides a quick overview. When users obtain the material flow data at national level, they may be interested in what percentage of non-metallic minerals or fossil fuel-based commodities comprise the DMI or DMC, as well as what causes the material flows and the associated environmental and economic concerns. More detailed industry level information can provide answers to these questions because most of SMM practices are implemented in industries. Knowing the industries of the greatest material throughput or of the greatest potential to improve resource efficiency, the government can develop the policies customized for these industries. Further refined analyses are required to provide industry level information, as detailed in the following subsection.

5.3. *Tracing life cycle stages of material flows among industries*

We developed three modules that allow refined data queries according to life cycle stages. As illustrated in Fig. 4a, the three modules are raw materials, industrial materials, and waste/recycling materials. The gateway page presents the pie charts that highlight the major materials, major industries, and major wastes. The interactive charts and tables of more details can be accessed upon entering each module.

The upper area of the raw material page shown in Fig. 4b illustrates the import and export trends for each of the four material categories. A click on one data point of the trend line would open a table showing the top ten high volume commodities of the corresponding raw material in the selected year. The imported or exported masses of the top ten raw material commodities are also quantified. In the middle area of the page, users can select a raw material to see the top five industries that consume the most of that material. Users can also select an industry to see the quantities of the four raw material categories that are consumed by the industry. The data of the raw materials consumed by industries is displayed in the lower area of the page. The datasets can be downloaded and allows professional users to use to develop their own analyses. This page will display more types of raw material applications in the future.

The trends shown in these modules span from 2006 to the latest year for which official data are available. As shown in Fig. 4c, the industry module informs users of the distributions of materials, waste generation, economic status, and input–output industrial analysis. In the upper area of the page, the system shows the raw material consumption and industrial waste generation of the industry selected by user. In the lower left area of the page, a chart responds to queries on the production trends (in monetary units) of a selected product of the selected industry. The lower right area of the page illustrates the driving forces of downstream sectors on the selected industry. For each query, the system presents a pie chart that shows the parts of the raw materials consumption by the selected industries due to the demands of all downstream industries. This information serves as a reference for supply chain management and resource efficient economic structure. Underneath in the chart areas, the data tables of the charts are available for personal analysis.

Fig. 4d shows the waste/recycling module, which generates extensive information regarding the wastes selected by users. The upper area of the page shows both the generation of the selected waste generation over time and the amounts generated by different industries. In the middle left area, a bar chart compares all kinds of wastes generated by a key industry that also utilizes the selected waste, to inform users that there could be other wastes more critical to this industry than the selected waste. In the middle right area, a pie chart includes all of the downstream industries, which purchase specific supply from the upstream industries generating the selected waste. This chart can provide insights to supply chain management for waste prevention. In the lower left area, the industries that reuse the waste as a secondary resource are plotted on a bar chart according to their consumption of the waste. Based on this chart, the government can identify various industrial reuse patterns, as a knowledge base to promote existing practices to reduce the wastes.

All the charts are designed for simple and interactive user experiences. The pie chart lists the top five industrial sectors, and other sectors are aggregated, as indicated on the chart. Users can cross-analyze sectors of interest through the raw material or waste pie charts by clicking on the industry component. For certain industrial wastes that can be used in civil engineering, the reuse quantities associated with different kinds of constructions are shown in the trend lines. Currently, coal fly ash and electric arc furnace slag are reused and reported this way on this system.

6. Conclusions and outlooks

SMM requires multidisciplinary knowledge of various materials, industries, and waste types. The SMM system introduced in this paper is developed to engage experts and concerned groups to develop SMM strategies collaboratively. The collaboration is difficult when the stakeholders have different level of understanding of the complicated material flow systems in the economy. This SMM information system thus provides a platform for all stakeholders to access comprehensive material flow information. The novelty of this system to other existing material flow information systems has two parts. While most of the existing systems provide national level indicators, this system can serve the analysis functions of industry level material flows according to the material input or waste output selected by the user. In addition, this system can model the driving forces from the upstream sectors that cause resource consumption and waste generation indirectly according to life-cycle perspective. With this information, the SMM policy makers may target the sectors with higher embodied resource footprint or waste footprint to achieve the SMM goal for efficiently resource use and waste prevention.

As a first information system support SMM, the web-based charts of material flow indicators may help raise public's awareness, motivation, and participation. Effective SMM requires the cooperation of experts in different fields. The proposed information system can better catch the attention of those with the expertise relevant to SMM. When the material flow information is placed on the web, more stakeholders can know and may care about the performance of a country's resource efficiency. Also, stakeholders may be easier to discuss and develop practical SMM measures based on a consistent and comprehensive knowledge base.

The proposed applications, based on WIO modeling, illustrate resource and waste streams from a supply chain perspective. Using the web technology, data can be visualized in interactive charts that can extract knowledge from massive amounts of information. Users can more easily gain insights from the filtered and summarized information. The decision makers or policy makers can also gain an understanding of the relevant supply chains for the implementation of waste prevention and resource footprints reduction.

We have seen several limitations of the information system to reach expected influences on successful SMM. First, the data used are not complete. The waste flows shown on the system may cover 80–90% of industrial waste generation because many smaller businesses do not report their waste generation to the government. Second, current macro-level indicators may only offer implications to government and the experts good at resource-economics. To engage more SMM stakeholders, the information and indicators at industrial and business level would be required for various SMM practitioners. For more applicable information, this system is under planning to develop other applications, which can render meso-level indicators for an individual sector and micro-level indicators for an individual facility. For example, the functionality of a web-based tool developed under US EPA's WasteWise, is considered in the future improvement to help corporations manage material flow data and track their SMM performance.

Third, the resource productivity is only applied to total material throughput. However, the selection of critical materials would refer to the economic importance of materials. Therefore, there should be a model capable of linking economic activities to the flows of different materials and calculate the economic relevance or resource productivities for specific materials.

In addition, the SMM system will be improved to provide more environmental information. Regarding the environmental impacts of materials, the system can only evaluate the impacts of waste generation and resource consumption. Selection of critical materials for SMM might involve the consideration of many environment impacts because each material has a distinct life cycle and associated environmental impacts. Drawing on a life cycle assessment based methodology to calculate the environmentally weighted material consumption [30], the weightings of impacts per kg of resources are estimated based on Ecoinvent database [31]. When the data of environmental weightings are established and integrated to the system, the decision makers in different government agencies can rank criticality of materials based on mass, economic importance, or ecological concern.

In summary, the applications developed in this SMM system can retrieve data from various databases and organize it for observing the material flow systems associated with economic activities. The data integration and data processing can guarantee the consistency and reproducibility of the results of indicators, material flow modeling, and scenario forecasting of waste generation over the long term. Using an advanced SMM information system, the decision makers for SMM can see the materials of high priority. Thus, the SMM practices may develop in focus at national, industrial or business level.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.serj.2017.02.001.

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