Estimating consistent Physical Supply-Use Tables (PSUTs) considering data uncertainties

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Abstract

In the context of decoupling resource consumption and environmental impacts from economic growth, more and more interest is devoted to comprehensive accounting of anthropogenic material flows within the economy and with the natural environment. Here, the field of PSUTs, considered as a general framework for physical data integration and environmental-economic modelling, comes to play. PSUTs estimation, including data compilation and mass balancing, generally shows two main limitations: it requires large scale and time-consuming efforts, while the uncertainty associated with the resulting tables is most often not addressed.

This work presents a numerical method to estimate consistent PSUTs considering data uncertainties. It allows all relevant information to be used in the PSUTs estimation process, including potentially large-data errors depending on the data quality. The mass balancing identities (input = output), in terms of products and activities, are used in a mathematical technique which fulfills all requirements of a typical constrained optimization technique: Data reconciliation.

According to the theoretical framework defined in this work [Schmidt et al., 2010], consistent PSUTs are estimated for France for the year 2006 as a case study. Such an approach calls for data reconciliation of various sources of information in estimating consistent PSUTs. It reduces the time for their estimation, considering all information in the most efficient manner possible while at the same time improving their reliability. This example suggests that the numerical method provides a promising approach for estimating consistent PSUTs considering data uncertainties.

Keywords: Constrained optimization problem, Data accuracy, Data reconciliation, Physical Supply-Use Tables (PSUTs), Uncertainty

INTRODUCTION

National, European or international environmental policies have increasingly emphasized the need to drive production and consumption of economic goods towards less consumption of raw materials and less emissions of pollutants and waste [OECD, 2001; European Commission, 2003; European Commission, 2010; Giljum et al., 2005]. The objective is to decouple – to break the link between – the economic growth and environmental pressures. In this context, deriving precise information on physical flows at the scale of an economy is crucial to evaluate the effectiveness of policies and to help determining new relevant actions to be taken.

As part of the developments in the field of material flow accounting, Physical Supply-Use Tables (PSUTs) depict anthropogenic material flows within the economy and in interaction with the natural environment. They complement the corresponding monetary tables (Monetary Supply-Use Tables, MSUTs) by registering flows of physical products, extraction of materials from nature, supply and use of wastes, emissions to nature and stock changes [Giljum et al., 2009; Gravgård Pedersen, 2006; Hoekstra and van den Bergh, 2006]. PSUTs are the necessary step before deriving Physical Input-Output Tables (PIOTs), which can be used for obtaining additional environmental information and for environmental modelling [Hoekstra and van den Bergh, 2006].

PSUTs are usually compiled based on data from different sources and are in some cases obtained from rough assumptions in the absence of more accurate information. Their future development faces two main limiting factors. Firstly their estimation, including data compilation and mass balancing, requires large-scale and time-consuming efforts. Secondly the uncertainty associated with the resulting tables is most often not addressed whereas it may be significant. Based on the review of five studies for which the compilation procedure is sufficiently documented, [Beylot et al., 2012] observe that both the data inventory and the treatment of inconsistencies are considered differently from one study to another whereas they are of core importance in estimating PSUTs.

Consequently, a systematic approach appears necessary to allow the user to estimate consistent PSUTs considering data uncertainties. In that context, this work proposes to reconcile all data related to PSUTs compilation, by including potentially the uncertainty depending on some knowledge about the accuracy of the values of the measurements. It should in principle estimate consistent PSUTs, making tables compilation more relevant and cost-effective while at the same time improving their reliability. Such an approach has been developed by the writers of the present paper.

The whole paper is organized as follows. After this introduction, describing the problem and enlightening the difficulty for estimating consistent PSUTs, the second section is devoted to recalling the PSUTs principles [Schmidt et al., 2010]. A theoretical framework of PSUTs compilation is presented in the third section through a well-documented procedure for the PSUTs compiled for France for the year 2006. Then, the proposed cost-saving strategy consisting of data reconciliation is described. It may be formulated in a recurrent fashion: a typical constrained optimization problem. In the fifth section, the proposed strategy is applied to two case studies. It is shown how the proposed strategy estimates consistent PSUTs considering data uncertainties and reduces the estimation time. Finally, conclusions, including a discussion on the limits of the presented method, and perspectives are presented as an illustration for future studies.

PHYSICAL SUPPLY-USE TABLES (PSUTs)

Theoretical framework

The framework of PSUTs, including their accounting identities, has been widely detailed in the literature, in particular by [Giljum et al., 2009; Hoekstra, 2010; Hoekstra et al., 2006 and Schmidt et al., 2010]. We consider the latter's description and notations in what follows. Every table mentioned below corresponds to a specified period and geographical area (e.g. France for the year 2006).

The Supply matrix, V, of dimensions activities by products, reports the supply of products per human activity. The Use matrix, U, of dimensions products by activities, details the intermediary consumptions of products per human activity. Noting that V' (transpose of V) is used in figures and formulas in order to have the same dimension as the Use matrix (U). These two tables are completed by the Import and Export vectors, N and E, of dimensions products by one, which report the exchanges of products with the rest of the world. Finally the vector Y, of dimensions products by one, stands for the final consumption vector. This first set of tables is traditionally accounted for in monetary terms (in MSUTs) and is correspondingly reported in physical units in PSUTs.

PSUTs additionally include the environment as a source of raw materials (R matrix of dimensions resources by activities) and as a sink for residuals and emissions (W_v and B matrices of dimensions products by activities and emissions by activities respectively). Finally, W_u and ΔS, of dimensions products by activities, represent the use of residuals and the addition to stock of products and residuals respectively.

Table 1: Nomenclature

Nomenclature	
Symbol	**Meaning**
B	Emissions
E	Export
g	Activity total
MSUTs	Monetary Supply-Use Tables
N	Import
PIOTs	Physical Input-Output Tables
PSUTs	Physical Supply-Use Tables
q	Product total
R	Resources
U	Use
V	Supply
W	Residuals
x	Measurement
$\hat{x}$	Reconciled estimate
Y	Needs fulfillment
Greek letters	
ΔS	Stock changes
ω	Data accuracy
Subscripts	
u	Use
v	Supply

The accounting identities that structure the PSUTs are based on the material balance principle (Figure 1). On the one hand, on a product perspective (q):

$$V' + N = U + Y + E \tag{1}$$

And on the other hand, on an activity perspective (g'):

$$V' + W_v + B + \Delta S = U + W_u + R \tag{2}$$

Balanced PSUT	Activities	Import	Needs Fulfilment	Export	Total
Products	V'	N			q
Total	g'				

Products	U		Y	E	q
Stock changes	$-\Delta S$				
Supply of residuals	$-W_v$				
Use of residuals	W_u				
Resources	R				
Emissions	-B				
Total	g'				

Figure 1: Theoretical framework for balanced PSUTs [Schmidt et al., 2010]

COMPILING PSUTs FOR FRANCE 2006

PSUTs compilation is mainly driven by the availability of statistical data. The latter generally originate from different sources and are in some cases completed with rough assumptions in the absence of more accurate information. This is in particular the case for the PSUTs compiled for France 2006 which will be briefly explained in what follows.

Data inventory

Material flows are reported in dry masses: water is excluded from the accounting. The economy is divided into 7 activities and their corresponding products. This partitioning is sufficient to highlight some relevant aspects of physical material flows within the economy, but remains at the same time coarse enough to clearly illustrate the data reconciliation technique. PSUTs include stocks variations, waste generation, use of waste, use of resources and emissions (Table 2). These extensions are neither partitioned into fractions (for waste) nor into substances (for emissions and resource uses) for the sake of clarity. The objective of this study is indeed not to calculate environmental pressures associated to the production of economic goods – which would for example require distinguishing between emissions of very distinct environmental impact potentials such as CO2 and N2O – but to illustrate the data reconciliation procedure.

Supply Table

1. Diagonal supplies of primary and secondary activities are estimated based on statistical data:
    - in *mass*: considering 3 activities ("agriculture, forestry and fishing"; "mining and quarrying" and "extraction and production of fuels, distribution of energy"), the diagonal supply is obtained by aggregation of annual data on domestic production, reported in mass for the year 2006 for a number of items corresponding to the product category [FAOSTAT, 2012; IFEN, 2009; DGEC, 2009; MEDDTL, 2012].
    - in *units other than mass*: the diagonal supply of "Manufacturing" activities is also obtained by aggregating statistics of annual domestic production for a number of items corresponding to the product category [SESSI, 2008]. However in this case a significant number of values are reported in volume units, in surface units or in "number of items", but not in mass units. These data need to be converted in terms of masses by use of conversion factors, either taken from [Daxbeck et al., 2009] or based on own assumptions.

In the case of the "construction" sector, no specific data is available on supplies. The diagonal supply is therefore roughly estimated by summing up part of the uses of the activity. Finally, "Service" and "Waste treatment" activities do not deliver any diagonal physical supply.

2. Off-diagonal supplies are estimated by converting data from monetary units to mass units by using the price as conversion factors. Data in monetary units are extracted from the Eurostat Supply table in its "59 activities per 59 products" framework [Eurostat, 2012] and further aggregated to comply with the "7 activities per 7 products" framework of this study. The import commodity price per unit of mass is used as a surrogate for the conversion factor and is calculated by aggregating Eurostat monetary and physical statistics on imports for the corresponding product category [Eurostat, 2012]. In the specific case of the co-production of "construction" products, the price per unit of mass supplied is used as a surrogate. It is roughly estimated by dividing the monetary diagonal supply of the "construction" activity by its corresponding physical value.

Finally, considering the "waste treatment" activity, Eurostat data [Eurostat, 2012] on recycling are used to estimate the corresponding off-diagonal supply of "mining and quarrying" products and "manufacturing" products.

Use Table

The annual consumption of fuels is available for most activities in mass units for the year 2006 [Eurostat, 2012]. These data are aggregated to comply with the framework of the Use table. On the contrary, in the cases of "agriculture, forestry and fishing" products, "mining and quarrying" products and "manufacturing" products, no mass data is available on their use by activities. Therefore the data on use reported in monetary units in the Eurostat annual Monetary Use Table are converted into mass units through the export commodity price per unit of mass as a surrogate. The latter is calculated by aggregating monetary and physical statistics on exports [Eurostat, 2012; FAOSTAT, 2012]. In the specific case of "construction" products, the price per unit of mass supplied is used as a proxy. Finally no mass is associated to the use of "Service" and "Waste treatment" products.

Imports, exports and final demand

Data of imports and exports are reported in mass in Eurostat and FAOSTAT databases [Eurostat, 2012; FAOSTAT, 2012] and are aggregated to comply with the 7 products of the tables' framework. The vector of final demand is obtained by converting its monetary version [Eurostat, 2012] into mass by use of the export commodity price per unit of mass.

Stock variations and waste generation

The mass of waste generated per activity in the year 2006 reported in Eurostat statistics [Eurostat, 2012] corresponds to the mass of waste directly generated by the annual consumption of the activity plus the mass of waste associated to stocks degradation. These data are used as an estimate for the mass of stocks variation plus waste generated per activity. In the specific case of the "waste treatment activity", waste landfilling is accounted for as a stock variation.

Use of waste

Only the waste treatment activity is considered to use waste. The corresponding value is estimated with data on waste treatment for the year 2006 [Eurostat, 2012].

Use of resources

Resources consumed by the activities "agriculture, forestry and fishing", "mining and quarrying", "manufacturing" and "extraction and production of fuels, distribution of energy" are estimated by multiplying the amount of products supplied (or part of this amount) by an estimated ratio to account for losses. "Construction", "Service" and "Waste Treatment" activities do not consume resources directly.

Emissions

Annual emissions of CO_2, CH_4, N_2O, NOx, CO, SO_2, and NMVOCs are extracted from UNFCCC reports [UNFCCC, 2012]. CO_2 emissions due to fuel combustion are recalculated considering the amount and type of fuel consumed by the activity (in the Use table), and emission factors in kg CO_2/kg fuel. The mass of emissions reported in the table only accounts for substances bounded to products and raw materials (e.g. only carbon is accounted for in CO_2 emissions). In the case of "agriculture, forestry and fishing", CO_2 emissions due to animal respiration are estimated based on the amount of cattle, as detailed in [Hafner et al., 2010].

Conversion from wet to dry masses

Mass data in national, European or sectorial statistics correspond to the wet mass of products and waste. They are converted into dry masses by use of the products water content as estimated in [BRGM, 2010].

Inconsistency

In spite of all efforts on compiling real-preliminary measured values, it has to be expected that inconsistencies in the mass balancing remain. Every differences between product (q) and activity (g') totals point to an inconsistency underlying the inherent uncertainty associated to the measured values (Table 2). Using erroneous data for accounting analysis and decision-making may yield distorted conclusions and result in improper decisions.

A research problem, which has not yet found its final solution, is how to reconcile various sources of information in estimating consistent PSUTs, whereas making PSUTs more relevant and cost-effective while at the same time improving their reliability [Beylot et al., 2012]. In our knowledge, no general theory or useful mathematical programs are available; however, it is very important to follow a systematic approach to estimate consistent PSUTs, leading therefore to betters sets of statistics to properly evaluate policies and help determining new relevant actions. This is the purpose of the present paper.

Supply (V')		**Activities**							**Imports**	**Total (q)**
		Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment		
Products	Agriculture, forestry and fishing	129 604	0	0	0	0	1 058	0	7 865	**138 527**
	Mining and quarrying	0	452 000	0	0	218	6	149 805	37 413	**639 443**
	Manufacturing	5 110	0	603 050	269	33	656	23 140	94 351	**726 609**
	Extraction and production of fuels. Distribution of energy	0	0	639	131 144	0	1 315	195	171 794	**305 087**
	Construction	0	0	0	0	466 152	2	0	0	**466 155**
	Services	0	0	0	0	0	0	0	0	**0**
	Waste treatment	0	0	0	0	0	0	0	0	**0**
Total (g')		**134 715**	**452 000**	**603 688**	**131 413**	**466 403**	**3 037**	**173 140**	**311 424**	

Use (U)		**Activities**							**Final consumption**	**Exports**	**Total (q)**
		Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment			
Products	Agriculture, forestry and fishing	48 300	0	96 023	639	4 748	5 468	0	68 869	31 470	**255 517**
	Mining and quarrying	3 953	6 488	95 878	69	439 000	2 627	184	4 620	13 230	**566 050**
	Manufacturing	5 277	672	133 211	1 258	27 152	33 175	3 550	82 307	84 418	**371 020**
	Extraction and production of fuels. Distribution of energy	3 549	148	31 528	155 918	1 321	91 546	559	23 334	27 173	**335 075**
	Construction	469	93	3 247	5 755	56 043	35 018	82	0	0	**100 708**
	Service	0	0	0	0	0	0	0	0	0	**0**
	Waste treatment	0	0	0	0	0	0	0	0	0	**0**
Total (U)		**61 548**	**7 402**	**359 887**	**163 638**	**528 264**	**167 834**	**4 374**	**179 130**	**156 291**	

Stocks changes (ΔS) and Supply of residuals (Wv)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment
Stock changes & Supply of residuals	2 839	1 034	21 368	1 190	233 440	24 158	111 587

Use of residuals (Wu)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment
Use of residuals	0	0	0	0	0	0	300 537

Resources (R)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment
Resources	173 897	497 200	25 576	2 770	0	0	0

Emissions (B)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment
Emissions	21 978	124	41 809	21 803	1 116	74 210	1 737
Total (g')	**210 628**	**503 443**	**322 286**	**143 415**	**293 708**	**69 466**	**191 588**

Table 2: Tentative PSUTs compiled for France 2006, before data reconciliation (values are given in kilotonnes)

ESTIMATING CONSISTENT PSUTs CONSIDERING DATA UNCERTAINTIES

A possible efficient way to estimate PSUTs is to reconcile data, including potentially the uncertainty depending on some knowledge about the accuracy of the values of the measurements.

Data reconciliation: A cost-saving strategy for estimating PSUTs considering data uncertainties

Data reconciliation is a technique that has been developed to improve the reliability of measurements by reducing the effect of random errors in the data. The principal difference between data reconciliation and other filtering techniques is that data reconciliation explicitly makes use of mass balance identities and obtains estimates of the variables by adjusting measurements so that the estimates satisfy the mass balance constraints. The reconciled estimates are expected to be more accurate than the measurements and, more importantly, are also consistent with the known relationships between variables and as defined by the constraints [Narasimhan et al., 2000].

Accurate data is, therefore, essential for analyzing any mathematical model. One measure of data inaccuracy is the consistency with regard to the mathematical models describing a system. Among the more classical models used for describing a functioning are the balance relationships, such as: mass, component, species, enthalpy, etc. PSUTs provide an ideal framework for ensuring consistency of data obtained from different sources and in some cases from rough assumptions (Equation 1 & 2). If this model is structurally perfectly known, it depends on measured data which are inherently uncertain. Therefore, it becomes very hazardous and mathematically not correct to reconcile data with regard to an uncertain model without taking this last fact into account [Maquin et al., 2000]. Assuming some knowledge about the accuracy of the values of the measurements (data accuracy), we propose to include this information in the reconciliation procedure. Data accuracy is then information to data reconciliation that has been included to consider uncertainty.

Data accuracy

Accuracy of the values of the measurements (ω_i) is assessed by the "expert judgment" of the authors considering both the relative quality of the data source and the potential need for data derivation by calculations (including data aggregation, conversion from one unit to another, estimation and calculation of conversion factors). Obviously, data accuracy are unrefined estimations, they are there only to give general trends. In our knowledge, this type of study has never been reported in the field of PSUTs. The study of these estimations can seem of course debatable, because it heavily depends on the "expert judgment". The ideal situation would be to perform the study using several judgments with different experts and to take the mean values, but it is out of the framework of this paper. The only goal of this study is to draw some general trends, and not clear-cut conclusions.

By considering the well-documented PSUTs compiled for France 2006 (Table 2), a "weighting factor" is associated to each data implemented in tables to account for its relative higher or lower degree of accuracy (Table 3). The "weighting factors" range from 0 to 1, 0 and 1 standing for the lowest and best accuracies respectively. As an illustration, we briefly present below data accuracy and the way the corresponding "weighting factors" are assigned to PSUTs compiled for France 2006. .

- *Data extracted from statistics in mass* are of high accuracy compared to other types of data used for PSUT compilation. Uncertainty is in that case mainly associated to data reporting and aggregation operations. Two groups of data reported in mass units should be however distinguished in the determination of their "weighting factors". In the first group the frameworks of statistics and PSUT, and their corresponding nomenclatures, can be easily linked. The relative accuracy of data is high, as reflected by "weighting factors" close to 1 as is for example the case for the supply and use of fuels. The second group of data is characterized by a doubt in the correspondence between statistics and tables: the "weighting factor" is set closer to 0 (e.g. considering stocks variations and waste generation).

- *Data extracted from statistics in physical units other than mass* (e.g. in “number of items”) and converted into mass units are given a relatively low degree of accuracy. In that case conversion factors are in most cases rough estimates. For example converting the number of pairs of shoes annually produced at the scale of a country into a mass (e.g. in tons) requires setting an average mass per pair of shoes. This conversion factor is necessarily inaccurate at the scale of a country production and adds a significant uncertainty to the calculated data.

- *Data converted from monetary units to mass units* by use of imports/exports prices are also given a relatively low degree of accuracy. Indeed the composition of products imported/exported may not be comparable to the composition of products supplied or consumed by the activities of the economy. The prices of imports/exports used as surrogates for the conversion can only result in rough estimates, whose inaccuracy is taken into account by “weighting factors” relatively close to 0.

- *Data for which the conversion from wet to dry mass is influent* (e.g. considering the supply of products of “agriculture, forestry and fishing”) and for which the product water content is highly inaccurate are associated a lower accuracy.

- *Emissions* are highly correlated with fuel consumption, due to the correlation between CO_2 emissions and fuel consumption and to the large share of CO_2 emissions in the total amount of emissions. The corresponding “weighting factors” account for this correlation.

- Finally, *data estimates* for “resource uses” and for the diagonal supply of the “construction” activity are based on assumptions and not on statistical data. They are therefore given the lowest degree of accuracy.

There is a relatively good confidence on the ranking of data as a function of their accuracy. For example data extracted from statistics in mass are globally given a higher “weighting factor” than physical data obtained by conversion of monetary data. However, the values associated with this accuracy, and more specifically differences between the degrees of accuracy of data, are less accurate and is it uncertain.

Supply (V')		**Activities**							**Imports**
		Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment	
Products	Agriculture, forestry and fishing	0.60	0.05	0.05	0.05	0.05	0.05	0.05	0.60
	Mining and quarrying	0.05	0.90	0.05	0.05	0.05	0.05	0.20	1
	Manufacturing	0.05	0.05	0.10	0.05	0.05	0.05	0.20	1
	Extraction and production of fuels. Distribution of energy	0.05	0.05	0.05	0.90	0.05	0.05	0.05	1
	Construction	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
	Services	0	0	0	0	0	0	0	0
	Waste treatment	0	0	0	0	0	0	0	0

Use (U)		**Activities**							**Final consumption**	**Exports**
		Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment		
Products	Agriculture, forestry and fishing	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.60
	Mining and quarrying	0.05	0.05	0.05	0.05	0.70	0.05	0.05	0.05	1
	Manufacturing	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1
	Extraction and production of fuels. Distribution of gas, electricity and steam	0.90	0.90	0.90	0.90	0.90	0.05	0.05	0.90	1
	Construction	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0	0
	Service	0	0	0	0	0	0	0	0	0
	Waste treatment	0	0	0	0	0	0	0	0	0

Stock changes (ΔS) & Supply of residuals (Wv)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment
Stock changes & Supply of residuals	0.01	0.02	0.02	0.02	0.02	0.02	0.02

Use of residuals (Wu)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment
Use of residuals	0	0	0	0	0	0	0.07

Resources (R)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment
Resources	0.01	0.01	0.01	0.01	0	0	0

Emissions (B)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment
Emissions	0.01	0.20	0.20	0.20	0.20	0.10	0.05

Table 3: Accuracy estimation for the tentative PSUTs compiled for France 2006

It is worth noting that if something appears to be implausible; one has to look for an acceptable explanation by analyzing the underlying sources and discussing the data with experts in the concerned area [Eurostat, 2008].

In that context, the cost-saving strategy proposes to include data accuracy to the data reconciliation procedure in order to estimate consistent PSUTs considering data uncertainties. The originality of the proposed strategy is to include all information about measured values into a mathematical model which can be easily applied for estimating consistent PSUTs.

A typical constrained optimization approach

At the start of estimating consistent PSUTs, a measured value is available for every entry of the PSUTs. By considering that the measurements are expected to be real-preliminary values, we can impose the condition that the differences between the measured and estimated flows should be as small as possible so that they satisfy the mass balance identities. Then, the cost-saving strategy can be formulated by the following constrained weighted least-squares optimization problem (Equations 3 & 4):

$$Min \sum_{i=1}^{n} \omega_i \left(\frac{x_i - \hat{x}_i}{x_i}\right)^2 \tag{3}$$

Subject to:

$$g_k(\hat{x}_i) = 0 \quad k = 1, \dots, m \tag{4}$$

The objective function (Equation 3) defines the total weighted sum square of adjustments made to measurements, where ω_i is the weight that reflects the data accuracy, x_i is the measurement and $\hat{x}_i$ is the reconciled estimate for variable x_i. Equation 4 defines the set of model constraints (i.e. material mass balance). The deterministic natural laws of conservation of mass (or energy for process engineering) are typically used as constraints for data reconciliation because they are usually known. These types of constraints that are imposed in reconciliation depend on the scope of the reconciliation problem. Furthermore, the complexity of the solution techniques used depends strongly on the constraints imposed. For example, if we are interested in reconciling (1) only the mass flow rate as stated in this paper or, (2) both the mass flow rates and the material content per material category, then the material balances constraints are linear in the mass flow variables, and a linear data reconciliation problem results. On the other hand, if we wish to reconcile process data (e.g. temperature or pressure measurements along with flows) then a nonlinear data reconciliation problem occurs.

The reconciliation problem is thus a constrained optimization problem (Figure 2) with the objective function given by Equation 3 and the constraints given by Equation 1 & 2. The solution of this optimization problem can be obtained mathematically for flow reconciliation by means of the solver fmincon of the MATLAB toolbox.

The proposed cost-saving strategy is based on the assumption that random errors are present in the account measurements which follow a normal (Gaussian) distribution, with zero mean and a known variance-covariance. In order words, if we denote the true value of the flow rate i by the variable x_i and the corresponding measured value by $\hat{x}_i$, then we can relate them by the Equation 5, where ε_i is the random error in measurement $\hat{x}_i$.

$$\hat{x}_i = x_i + \varepsilon_i \quad i = 1 \dots n \tag{5}$$

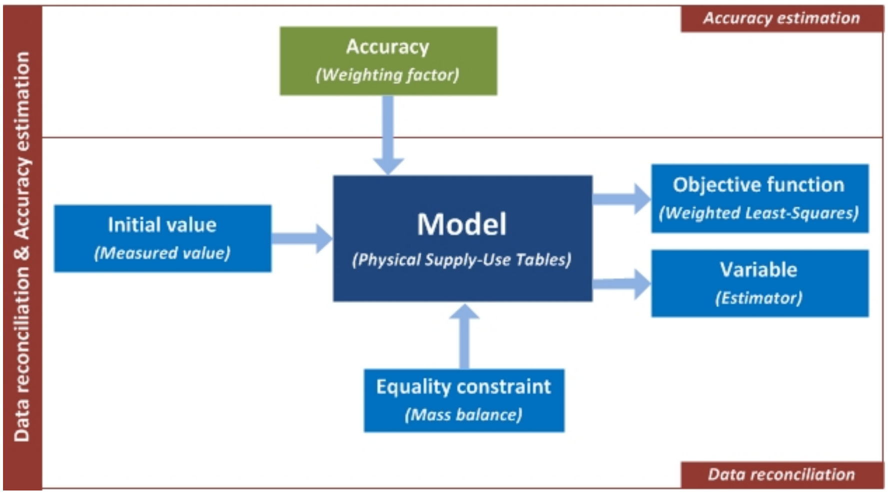

Figure 2: A typical constrained optimization approach applied to PSUTs estimation

Additional available information

As the philosophy behind the proposed cost-saving strategy involves using all available relevant information, the typical constrained optimization approach can be extended to situations where there are different kinds of prior information. Additional information in connection with the PSUTs estimation can be:

1. Information of measured values boundaries,
2. Moments constraints in the form of product (q) or activity (g') totals,
3. Inequality constraints related to product (q) or activity (g') totals,
4. Information on empty cells (zeros) and,
5. Information on measurements errors.

Thereby, all available relevant information can be incorporated in to estimate consistent PSUTs considering data uncertainties.

CASE STUDY

In order to obtain a good understanding of the issues in data reconciliation for future more complex problems (e.g. full PSUTs compiled for France 2006), a well-documented case study is introduced here (PSUTs compiled for France 2006), in order to highlight the assumptions to estimate consistent PSUTs considering data uncertainties.

PSUTs compiled for France 2006

Problem description

Let us consider the PSUTs compiled for France 2006. All mass flow rates are compiled as described in the section: Compiling PSUTs for France 2006. According to [Schmidt et al., 2010], physical flows compiled for France 2006 are presented as shown in Figure 1: Supply (V'), Use (U), Imports (N), Exports (E), Stock changes (ΔS), Needs fulfilment (Y), Supply and Use of residuals (W_v and W_u), Emissions (B) and Resources (R).

Flows must fulfill the balancing identities presented in Equations 1 & 2. It means that product (q) and activity (g') totals do not balance. Every difference points to an inconsistency underlying the inherent uncertainty associated to the measured values. Obviously, the flow measurements contain unknown random errors (Table 2).

Problem solution

Then, it is desired to derive estimates of the flows that satisfy the mass flow balances (Equations 1 & 2). Initially, we assume that the differences between the measured and estimated flows, also referred to as adjustments, should be as small as possible since the measurements are expected to be real-preliminary values. Thus, the estimation problem is a constrained optimization problem with the objective function given by Equation 3 and the constraints given by Equations 1 & 2.

The solution of this optimization problem is obtained mathematically by means of the proposed cost-saving strategy: Data reconciliation.

Table 4 shows the reconciled flows for the PSUTs compiled for France 2006. The reconciled flows were obtained by assuming that all measurements are equally accurate (weights are all equal, $\omega_i = 1$).

Supply (V')		**Activities**								
		Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment	**Imports**	**Total (q)**
Products	Agriculture, forestry and fishing	185 341	0	0	0	0	1 066	0	8 036	**194 442**
	Mining and quarrying	0	364 189	0	0	218	6	120 610	34 828	**519 851**
	Manufacturing	5 074	0	296 252	269	33	657	22 236	78 406	**402 927**
	Extraction and production of fuels. Distribution of energy	0	0	639	135 920	0	1 322	195	154 095	**292 170**
	Construction	0	0	0	0	105 384	2	0	0	**105 387**
	Services	0	0	0	0	0	0	0	0	**0**
	Waste treatment	0	0	0	0	0	0	0	0	**0**
Total (g')		**190 414**	**364 189**	**296 891**	**136 189**	**105 635**	**3 053**	**143 041**	**275 365**	

Use (U)		**Activities**									
		Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment	**Final consumption**	**Exports**	**Total (q)**
Products	Agriculture, forestry and fishing	40 289	0	58 807	637	4 635	5 254	0	55 987	28 833	**194 442**
	Mining and quarrying	3 972	6 523	103 014	69	385 284	2 609	184	4 657	13 539	**519 851**
	Manufacturing	5 316	673	142 187	1 259	27 043	30 921	3 571	94 443	97 514	**402 927**
	Extraction and production of fuels. Distribution of energy	3 548	148	30 837	148 977	1 318	55 448	559	23 648	27 687	**292 170**
	Construction	470	93	3 276	5 858	61 137	34 470	82	0	0	**105 387**
	Service	0	0	0	0	0	0	0	0	0	**0**
	Waste treatment	0	0	0	0	0	0	0	0	0	**0**
Total (U)		**53 594**	**7 437**	**338 120**	**156 800**	**479 419**	**128 701**	**4 396**	**178 736**	**167 573**	

Stock changes (ΔS) & Supply of residuals (Wv)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment
Stock changes & Supply of residuals	2 843	1 035	21 959	1 191	372 664	26 716	109 707

Use of residuals (Wu)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment
Use of residuals	0	0	0	0	0	0	250 089

Resources (R)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment
Resources	161 936	357 912	24 680	2 764	0	0	0

Emissions (B)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment
Emissions	22 273	124	43 949	22 184	1 119	98 932	1 737
Total (g')	**190 414**	**364 189**	**296 891**	**136 189**	**105 635**	**3 053**	**143 041**

Table 4: Consistent PSUTs compiled for France 2006-kilotonnes ($\omega_i = 1$)

Noting that while the measured values (Table 2) do not satisfy the flow balances, Equations 1 & 2, the reconciled flows satisfy them (Table 4). Therefore it improves the benefits of handling inconsistencies manually by modifying coefficients of the PSUTs and makes PSUTs more relevant and cost-effective.

In practice, however, it is likely that some measurements are more accurate than other depending on the data accuracy. Nevertheless, such accuracy is generally not addressed to get consistent PSUTs [Beylot et al., 2012]. In order to account for this, the compilation procedure of the PSUTs compiled for France 2006 has been well-documented by considering data accuracy (Table 3). Therefore we propose to reconcile these tables, including potentially the uncertainty depending on the data accuracy. Thus, data reconciliation and data accuracy are applied together to estimate consistent PSUTs considering data uncertainties.

It takes into account the weighted least-square objective (Equation 3) as a more general criterion, where the weights (ω_i) are chosen to reflect the accuracy of the respective measurements. Then, the reconciled flows shown in Table 5 are obtained by assuming some knowledge about the accuracy of the values of the measurements.

Supply (V')		**Activities**							**Imports**	**Total (q)**
		Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of energy	Construction	Services	Waste treatment		
Products	Agriculture, forestry and fishing	137 296	0	0	0	0	1 071	0	7 896	**146 263**
	Mining and quarrying	0	415 796	0	0	218	6	120 302	37 254	**573 577**
	Manufacturing	5 006	0	400 154	269	33	657	22 534	92 027	**520 680**
	Extraction and production of fuels. Distribution of energy	0	0	638	135 630	0	1 323	194	167 841	**305 626**
	Construction	0	0	0	0	212 718	2	0	0	**212 721**
	Services	0	0	0	0	0	0	0	0	**0**
	Waste treatment	0	0	0	0	0	0	0	0	**0**
Total (g')		**142 302**	**415 796**	**400 792**	**135 899**	**212 969**	**3 059**	**143 031**	**305 019**	

Use (U)		**Activities**							**Final consumption**	**Exports**	**Total (q)**
		Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment			
Products	Agriculture, forestry and fishing	39 893	0	22 860	634	4 579	5 113	0	42 221	30 963	**146 263**
	Mining and quarrying	3 999	6 606	135 381	69	406 810	2 604	184	4 672	13 252	**573 577**
	Manufacturing	5 386	674	248 565	1 255	30 331	32 420	3 603	114 947	83 498	**520 680**
	Extraction and production of fuels. Distribution of gas, electricity and steam	3 550	148	31 632	148 751	1 321	69 079	559	23 370	27 216	**305 626**
	Construction	475	94	3 568	6 085	188 054	14 363	83	0	0	**212 721**
	Service	0	0	0	0	0	0	0	0	0	**0**
	Waste treatment	0	0	0	0	0	0	0	0	0	**0**
Total (U)		**53 304**	**7 522**	**442 006**	**156 794**	**631 095**	**123 579**	**4 429**	**185 211**	**154 928**	

Stock changes (ΔS) & Supply of residuals (Wv)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment
Stock changes & Supply of residuals	2 822	1 034	17 209	1 207	417 009	37 317	133 163

Use of residuals (Wu)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment
Use of residuals	0	0	0	0	0	0	273 500

Resources (R)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment
Resources	115 915	409 433	16 305	2 580	0	0	0

Emissions (B)	**Activities**						
	Agriculture, forestry and fishing	Mining and quarrying	Manufacturing	Extraction and production of fuels. Distribution of gas, electricity and steam	Construction	Services	Waste treatment
Emissions	24 095	124	40 310	22 268	1 117	83 203	1 735
Total (g')	**142 302**	**415 796**	**400 792**	**135 899**	**212 969**	**3 059**	**143 031**

Table 5: Consistent PSUTs compiled for France 2006-kilotonnes (by considering data accuracy estimation)

It can be easily verified that while the measured values do not satisfy the flow balances (Table 2), both consistent PSUTs satisfy them (Tables 4 & 5). Through a simple comparison between both consistent PSUTs (weights are equal and not-equal), it can be verified that considering data accuracy in the reconciliation procedure means that the adjustments made to measurements are more or less forced to be as small as possible in order to get consistent PSUTs. Including data accuracy has also a significant influence to respective values through the equality constraints (Equation 1 & 2).

Even though such cost-saving strategy produces consistent PSUTs, by reducing the time for their estimation while at the same time improving their reliability, it must be taken care about data accuracy since it could have significant influence during the reconciliation process. It should be kept in mind that using erroneous data for accounting analysis and decision-making may yield distorted conclusions and result in improper decisions.

A current study aims at identifying data accuracy influence by analyzing those measurements containing significant adjustments. A simple statistical test will be applied to determine in which confidence interval ($\pm 1\sigma, \pm 2\sigma \ or \ \pm 3\sigma$) the computed measurements adjustments fall in. Then, we can suppose that all measurement adjustments which fall into the $\pm 3\sigma$ confidence interval could be suspected of needing further consideration and, either modify them or make appropriate compensation to their accuracy estimation. This helpful technique is a sequential procedure for gross error detection and makes use of the statistical test known as the measurement test. A variety of statistical test and methods could be applied [Narasimhan et al., 2000] to obtain better sets of statistics.

In parallel with the analysis of the influence of data accuracy, future developments in the reconciliation technique applied to PSUTs should focus on the estimation of “weighting factors” which stand for data accuracy. These factors should account for the characteristics of each data source according to a procedure and a calculation path to be defined.

Finally future research should intend to apply this data reconciliation technique to a case-study at a more disaggregated level. The French PSUTs presented as a case study in this paper distinguish between 7 activities only. The level of data aggregation should be refined to account for specific products, emissions and resources for environmental modeling purposes.

CONCLUSIONS AND RECOMMENDATIONS

Despite PSUTs can be very useful to derive precise information on physical flows at the scale on an economy, their estimation, including data compilation and mass balancing, still requires large-scale efforts, whereas inherent uncertainty associated to measured data is generally not accounted for.

This work proposed that data have to be reconciled because they must adhere to the mass balance identities. In the reconciliation procedure, the confrontation of the data is made by considering uncertainty depending on some knowledge about the accuracy of the values of the measurements (i.e. the “expert judgment” of the authors).This leads to estimate consistent PSUTs and makes them more relevant and cost-effective

The proposed cost-saving strategy (i.e. data reconciliation) still enhances the benefits of handling inconsistencies manually by taking into account all information in the most efficient manner possible. Indeed, it could prevent from erroneous decisions. The estimation procedure is very simple to implement through a well-known typical constrained optimization problem. However, it must be taken care about including data accuracy because it could have significant influence during the reconciliation process. A current study aims to determine suspected values requiring further consideration and either modify them or make appropriate compensation to their data accuracy estimation.

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