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The effect of data structure and model choices on MFA results: A comparison of phosphorus balances for Denmark and Austria

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ABSTRACT

Material Flow Analysis (MFA) studies for a particular substance often exist for several different countries or regions, but share a similar goal and scope. In direct comparisons of such regional resource budgets, the importance of the choices made in establishing an MFA system tends to be disregarded.

We identify and quantify the effects of choices made in system layout, data material and uncertainty assessment on the outcome of regional MFAs using two recent country-scale MFAs (of Denmark and Austria) of phosphorus as a case study.

We highlight the differences in system boundaries and definition of flows and processes. We quantify types and choice of data sources; analyse the consistency of the data used by looking at the extent of data reconciliation, as a measure of model quality; quantify the effect of different approaches to uncertainty assessment; and show the influence of aggregating/disaggregating flows.

We show that differences in system layout are mostly attributable to varying goals and scope definitions. Direct comparison of uncertainties across studies is problematic: both studies draw on similar types of data sources, yet they show very different uncertainty assessments; the uncertainty assessment in MFA is always subjective to a certain extent. We demonstrate that reconciliation of conflicting data provides a useful measure to assess data consistency and model quality: data are more consistent (5% average change in reconciled data) in the Austrian than in the Danish (9%) case. We suggest an iterative approach to uncertainty assessment. Likewise, we demonstrate the effect of the aggregation of flows on model uncertainty.

These findings quantify and emphasise the importance of examining MFA studies' metadata and suggest an approach to be followed when drawing on such studies as a source of information.

1. Introduction

Material Flow Analysis (MFA; Baccini and Brunner, 2012) has become a widespread approach to visualise the anthropogenic turnover of materials across a defined geographical area. For a number of substances, e.g. phosphorus (P), several MFA studies – often called substance flow analysis (SFA) when studying a substance – of regional or national households with similar goal and scope definitions are available. Patterns of resource use are analysed to evaluate resource efficiency and recycling activities (e.g. Chen and Graedel, 2012), anthropogenic material stocks are investigated using dynamic analysis to quantify current and future resource potentials (e.g. Müller et al., 2014), and sources and sinks of problematic substances are the focus of MFA studies addressing environmental pollution issues (e.g. Hansen and Lassen, 2003). While MFA studies may obviously differ with respect to their geographical scope, the authors' modelling choices and the database used for MFA are a different set of factors often disregarded in the comparison of regional resource budgets. Country or multi-country level MFA studies are quite consistent with respect to system boundaries, and external trade and national accounts, across substances and countries (Fischer-Kowalski et al., 2011). For P, Seyhan (2009) suggests a standard template regarding processes, flows and system boundaries, for P resource budgets on the national or regional level.

However, there is considerable freedom in data selection and model choices. This implies that the model and data structure of an MFA typically vary from one study to another, an issue tending

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to get little mention in comparisons of P flow studies, which are often taken at face value (e.g. the review of phosphorus MFAs by Chowdhury et al., 2014). Data uncertainty quantification and consequent uncertainty analysis has become an integral part of MFA, and has recently been analysed in more detail by Laner et al. (2014, 2015b). Schwab et al. (2015) have moreover presented a detailed framework to systematically characterise data used in an MFA. Still, uncertainties due to model structure and scenario assumptions (or arbitrary choices of the practitioner), and their influence on MFA results, are rarely addressed and therefore difficult to analyse.

It is the aim of this work to examine the effect of the MFA system layout and modellers' choices on the outcome of regional MFAs, using the country-scale MFAs of P in Denmark and Austria as case studies. The Danish study (Klinglmair et al., 2015) examines the anthropogenic P budgets of three distinct regions in Denmark as subsystems of the P flows on the national scale. The Austrian study (Zoboli et al., 2015a) presents a 22-year timeline of detailed P budgets on the national level with particularly detailed accounts of flows in the waste management sector. Both studies share the objective of examining anthropogenic P flows from a standpoint of resource efficiency for countries of comparable size and population.

The following characteristics of an MFA model are of interest to the above objective: (1) system boundaries, layout (i.e. processes/flows shown, resolution, definition of processes, flow definitions), (2) types and choice of data sources, (3) the closely linked issues of data reconciliation and uncertainty assessment: over-determination, i.e. the difference between the number of independent balance equations and unknown variables (flows) of the model; the results of different approaches to quantify uncertainties in both studies; the extent of data reconciliation as a measure of data consistency and model quality; and the effects of aggregation/disaggregation of flows on model uncertainty. Points 1 and 2 are discussed in qualitative terms; point 3 consists of systematically quantifiable results. It is not the aim of this study to compare the P budgets of the two countries as such; instead, we take the specific examples of these two studies to illustrate, on a more general level, the extent of differences that can occur in the areas above due to the MFA practitioner, the data available, and the model formulation, apart from actual physical differences between the systems. In this way, we demonstrate a series of steps to analyse MFA studies in order to make plain, and quantify, this often-overlooked distinction. While this work is based on studies of P, the conclusions we draw may be applied to a wider range of country- or regional-scale resource budgets.

2. Materials and methods

2.1. Source material and background

The present study is based on two recent P balances (Klinglmair et al., 2015; Zoboli et al., 2015a) for Denmark and Austria, conducted at the Technical University of Denmark and Vienna University of Technology, respectively. Table 1 shows characteristics pertinent to the two countries' P budgets. The area used for agriculture is similar in both countries, but relatively smaller in Austria, due to the larger area of the country and the high share of forests. However, more livestock is produced in Denmark, with a particularly high number of pigs compared to Austria.

While the geographical scope and the areas under scrutiny are comparable, the objectives of the studies differ in their respective focus. In the Austrian case, Zoboli et al. (2015a) draw upon an existing P budget (Egle et al., 2014) to examine the utility of multi-year timelines in MFA studies, highlighting considerable variation in the period from 1990 to 2011. The model layout was only slightly

Table 1
Basic country data pertaining to P households in Austria (AT) and Denmark (DK).

		AT	DK
Population		8,200,000	5,580,000
Area	ha	8,387,899	4,309,400
Agricultural area	ha	2,879,000	2,567,000
	% of total	34%	60%
Forest area	ha	3,405,752	600,427
	% of total	41%	14%
Livestock	Cattle	1,976,527	1,567,970
	Pigs	3,004,907	12,931,678
	Sheep	361,183	143,889
	Horses	*81,637*	61,476
	Goats	72,358	(*no data*)
	Poultry	14,644,413	18,206,943
Livestock/ha agricultural land	Cattle	0.7	0.6
	Pigs	1.0	5.0
	Sheep	0.13	0.06
	Horses	*0.02*	0.02
	Goats	0.03	(*no data*)
	Poultry	28.8	7.1

modified from the earlier study, and comprises 56 processes and 122 flows, including 10 'virtual' processes to aggregate or split flows for visualisation purposes. 11 processes contain subsystems, where the process is further disaggregated into flows and processes on a sub-system level. The Danish study (Klinglmair et al., 2015), conducted for the year 2011, aims for a higher spatial resolution by incorporating three regional subdivisions, for the agriculture and waste management processes, into the national P balance. The purpose of this study was to investigate imbalances in the P household and potential for P recovery resulting from differences in agricultural practice, and population and industrial density between the Danish regions. The model layout comprises a total of 50 processes and 166 flows, including 12 'virtual' processes and 9 processes containing subsystems (see Tables S.1 and S.2 in the supplementary data for flows and data sources). For the purpose of this comparison, we look at the results for the year 2011 in both studies. Both systems are overdetermined, i.e. more variables (flows) are known than are necessary to solve the balance equations. In the Danish model, all 166 flows are determined, while all 7 stock changes are unknown and therefore calculated using mass balance equations. This means that there exist 7 unknowns for 41 independent balance equations (processes not containing a subsystem). In the Austrian case, 16 of 122 flows and 7 out of 8 stock changes are calculated, so that we find 44 independent balance equations and 23 unknowns. The degree of overdetermination is the number of independent balance equations (constraints) minus the number of unknown variables; the Danish model can therefore be said to be overdetermined to a higher degree. Fig. 1 shows simplified qualitative representations of both MFA systems. It has to be noted that several processes shown in the main system in the Austrian study (*animal husbandry*, *crop farming*, *forestry* & *miscellaneous soils*, and *bioenergy*; Fig. 1b) are found in sub-systems in the *agriculture* process in the Danish study (see Fig. 1a).

2.2. Material Flow Analysis (MFA)

Both studies use the STAN 2.5 software (Cencic and Rechberger, 2008) for balancing material flow systems with options of data reconciliation and uncertainty propagation, assuming all uncertain flows to be random, normally distributed variables given by mean value and standard deviation. Fig. 1 shows a simplified graphical representation of the two MFA models.

Since flow values are based on data of varying quality (and hence uncertainty) from multiple sources, these data will generally not be fully consistent with the model, but contradict each