Material Flow Analysis to Evaluate Sustainability in Supply Chains

Haroune Zaghdaoui, Anicia Jaegler, Natacha Gondran, Jairo Montoya-Torres

Preprints of the 20th World Congress
The International Federation of Automatic Control
Toulouse, France, July 9-14, 2017

Material Flow Analysis to Evaluate Sustainability in Supply Chains

Haroune Zaghdaoui*,**,***, Anicia Jaegler*, Natacha Gondran**, Jairo R. Montoya-Torres****

*Centre d'Excellence Supply Chain - Kedge Business School, 680 Cours de la Libération, 33400 Talence, France
(e-mail: haroune.zaghdaoui@kedgebs.com, anicia.jaegler@kedgebs.com)
**Ecole Nationale Supérieure des Mines de Saint Etienne, Institut Fayol, CNRS, UMR 5600 EVS, F-42023, France
(e-mail: gondran@emse.fr)
***Facultad de Ingeniería, Universidad de La Sabana, km 7 autopista norte de Bogotá, Chía, Colombia
(e-mail: harouneza@unisabana.edu.co)
****School of Management, Universidad de los Andes, Calle 21 # 1-20 Bogotá, D.C., Colombia
(e-mail: jr.montoya@uniandes.edu.co)

Abstract: The study of raw materials flows becomes a decision-making tool to improve the management of resources and to evaluate environmental issues from the producer's viewpoint to the consumer's one. This paper presents the Material Flow Analysis (MFA) method for evaluating sustainability in supply chains. In terms of decision-making, MFA can be used to analyze and improve the effectiveness of measures and to design efficient management strategies to improve sustainability in supply chains. This paper presents a preliminary overview of academic works related with the applications of MFA to the analysis of sustainability in supply chains. Literature is evaluated and classified according to certain criteria and opportunities for further research are identified.

Keywords: Material Flow Analysis; sustainable supply chains, evaluation of supply chains.

1. INTRODUCTION

Ecological issues are the subject of international debates at all levels of society (government, scientific, Non-Governmental Organizations...). It can be seen as the biggest challenge humanity has ever faced (GIEC, 2013). Today, the widespread awareness as well as regulations have led us to rethink the design of supply chains to incorporate the sustainability aspect. This should be analyzed by taking into account environmental, economic and social aspects (Amigun, Musango, & Stafford, 2011; Duku, Gu, & Hagan, 2011; Van Dam, de Klerk-Engels, Struik, & Rabbinge, 2005).

Among the different methods to evaluate sustainability in supply chains, Material Flow Analysis (MFA) has appeared as an effective approach. Indeed, as MFA studies the flow of resources used and transformed by a single or a combination of various processes, it is possible to identify the use of resources and emissions of wastes in the different processes and thus, identify environmental problems. MFA has the advantage to be applied and useful to different size of systems. For example, (Courtonne, Alapetite, Longaretti, Dupré, & Prados, 2015) applied MFA to compare regional to national cereal flows. At a higher level, (Giljum, Dittrich, Lieber, & Lutter, 2014) presented a MFA study on all countries world-wide. (Brunner & Rechberger, 2016) highlighted the need for balancing not only technical systems but also social and economic systems. This paper hence aims at presenting a preliminary review of academic works on the application of MFA for the evaluation of sustainability issues in supply chains.

The paper is organized as followed. Section 2 presents the research methodology, followed by principles of MFA. Section 3 is devoted to the application of MFA in sustainable supply chains, including the findings of the literature review. Conclusion and perspectives for further research are presented in Section 4.

2. METHODOLOGY

2.1 Research Methodology

Before starting the bibliographic research, it is important to identify the different elements needed: On which database are we going to make our research? Which keywords to use? How to classify the articles found?

Keywords were divided into three groups: the first set includes "Supply Chain" and "Supply Chain Management". As this study endeavors to analyze the sustainability of supply chains, the second group covers different keywords related to the sustainable aspect: "sustainability", green", "sustainable", "ecological". Finally, the last set is dedicated to the method used to evaluate sustainable supply chains: Material Flow Analysis. These keywords should appear in abstract, title or keywords of the articles. Searches were made within the Sciencedirect database. Then, to improve the efficiency of the research, these keywords were mixed (eg: "Sustainable Supply Chains" AND "MFA", both in ABSTRACT-TITLE-KEYWORDS).

About 100 articles were identified. Most of the articles were not related to MFA in supply chains and / or did not include the sustainable aspect. Hence, a manual selection was made to reduce the list to around ten papers, specifically related to MFA to assess sustainability in Supply Chains.

This research may be improved by looking for publications from other databases (Springer, Emerald, Wiley) but also by enlarging the set of keywords and tweaking the systematic strategy to identify relevant papers. This step will be realized in a future work which will deepen the analysis of each paper and extract the most relevant sustainable indicators. The objective is to build a MFA-based model which assesses simultaneously the three pillars of sustainability in supply chains.

2.2 Principle of MFA

According to (Brunner & Rechberger, 2016), Material Flow Analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time. In fact, the core principle of MFA is the mass balance, derived from Lavoisier's law of mass conservation (Lavoisier, 1789).

One of the many possible applications of MFA is to help with Sustainable Materials Management which is defined in (EPA, 2009) as "an approach to serving human needs by using/reusing resources most productively and sustainably throughout their life cycles, generally minimizing the amount of materials involved and all the associated environmental impacts". MFA may be used for different sizes of systems, from a company or a supply chain to a territory (city or Nation, for example). Some actors around the world are focusing on Sustainable Materials Management and trying to increase sustainability, but one of the first question is « where to start? ». Indeed, few smaller materials, coming from all over the world, are transformed into products and the tracing is complicated. MFA can help decision makers. However, since it only highlights a few issues, it should be used in conjugation with other techniques.

MFA aims (but not only) to improve environmental performance, reduce wastes, recycle products and improve operational costs. As stated in (Brunner & Rechberger, 2016; Hendriks et al., 2000), a complete Material Flow Analysis comprises the following steps:

- Definition of the objective of the MFA and the parameters considered
- Definition of the balance scope and the balance period
- Identification and definition of process steps and relevant flows and stocks.
- Drawing the flowchart
- Drawing up the balances
- Interpretation of the results

Depending on the objective, MFA has been implemented for scopes creating a family of methodologies ranging from Substance Flow Analysis to Economy-Wide Material Flow Accounting (Bringezu & Moriguchi, 2002).

MFA allows considering the three dimensions of sustainability: on the economic level, MFA helps to measure the creation of wealth; on the social level, it allows to consider social impacts and especially employment; finally, on the environmental level, it became an interesting tool to measure the different environmental pressures, from producers to consumers (Courtonne et al., 2015).

Figure 1 shows an example of a generic process to understand through an illustration the concept of MFA. For each step *i* of the process, the total flow entering should be equal to the total flow leaving it. The figure illustrates the MFA for a multi-period process. The index *j* is related to the period. For example: $LC_{i,j}$ means "Life Cycle stage *i* at the period *j*".

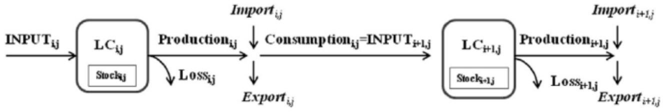

Fig. 1: Schematic diagram of mass balance for each stage (Sevigné-Itoiz, Gasol, Rieradevall, & Gabarrell, 2015)

MFA itself only evaluates the flows passing through a system. It should be combined with other specific sustainable methods as Life Cycle Analysis or Carbon/Water Footprint to evaluate the environment impacts of these flows.

3. MFA IN SUSTAINABLE SUPPLY CHAINS

3.1 Literature Review

As explained previously, MFA allows defining, with a better knowledge of the physical flows, a strategy for managing resources and reducing environmental pressures. (Courtonne et al., 2015) modeled Sankey diagrams to evaluate flows of cereals in France. Their study compares results get by a study at a national scale with another study downscaled at a regional level. Their first objective is to associate these flows to the major environmental impacts (energy use, GHG, etc.).

Many authors have argued that MFA should be coupled with other methods including social, economic and/or environmental models (Binder, 2007). For example, (Kytzia, Faist, & Baccini, 2004) developed the Economically Extended MFA or EE-MFA, an economic model coupled with MFA to study economic consequences of environmental policies.

It is also possible to combine MFA with an environmental model. The most common is Life Cycle Assessment (LCA) and its derivatives. For example, (Courtonne, Longaretti, Alapetite, & Dupré, 2016) used an Absorbing Markov Chain model to study the fate of French cereals and link worldwide consumptions to environmental pressures along the supply chain, that is, induced by production, transformation or transport. They coupled MFA with associated pressures on the environment all along the supply chain, using the LCA principles and database, to estimated Energy use, GHG emissions, land use, use of pesticides and blue water footprint that are generated by the cereal supply chain. (Sevigné-Itoiz et al., 2015) combined MFA and Consequential LCA to assess the effect recycling waste paper has on the production of new paper, and consequently, on the import and export of virgin pulp and finished products respectively. The CLCA method aims at rectifying the shortcomings of the MFA method in accounting for the changing global market scenario by assessing the life cycle of various elements being used in the process and their sources. (Widok, Schiemann, Jahr, & Wohlgemuth, 2012) used MFA as an integrated part of a simulation software that couples Discrete Event Simulation (DES) and LCA, a combination which refers back to (Wohlgemuth, 2005). One of the main benefit of this approach was to analyze the environmental impacts of economic changes and vice versa. The project aimed at integrating the social aspects to balance the three pillars of sustainability. So, the LCA can be considered as an impact assessment tool of MFA results.

In another field, (Pirani & Arafat, 2016) used the MFA to evaluate the food waste management in the hospitality sector. They also calculated Water and Carbon footprints for benchmarking. They found that, depending on the type of service (buffet, a la carte, breakfast…), wastes could drastically vary. Thus, they concluded that breakfast was the most sustainable event and services similar to buffet generates the biggest amount of waste. This study shows that in order to reduce food waste in hospitality sector, fundamental changes should be realized in terms of how this sector operates and how guests perceive these changes.

The European Strategy for Environmental Accounting (ESEA) identifies Economy-Wide Material Flow Accounts (EW-MFA) as one core module of Environmental Accounts to be produced regularly and in a timely fashion in order to support policy making (Eurostat, 2013). Based on this method, (Giljum et al., 2014) conducted a research which assesses world-wide patterns of material operations (extraction, trade, consumption and productivity). The research covers used materials for all countries world-wide between 1980 and 2009. Authors concluded that global resource extraction and consumption increased considerably in the past 30 years, especially for Asia who played the most important role (half of all globally extracted materials in 2009). Based on the data underlying their paper, they also concluded that the world is not on a track towards "greener growth" or a "green economy".

The biggest challenge authors face when applying MFA is the uncertainties on data. Traditionally, MFA is performed based on statistical approaches and model-based approximation. (Kuczenski, Geyer, Zink, & Henderson, 2014) achieved a distinct MFA study as their main results derives from a collection of direct observations. They argued that using data collected from direct observation can potentially increase the relevance of MFA.

3.2 Findings

Selected papers were classified according to the following criteria: methodology used, sustainability indicator (economic, environmental and social) and industrial sector of application. Afterwards, a deeper analysis of performance metrics is carried out. Table 1 presents this first classification of papers. A nomenclature is presented in appendix to define the different acronyms used.

	Methodology used	Environmental	Economic	Social	Sector
(Courtonne et al., 2015)	Downscaling MFA using SUT	x			Food (cereals)
(Courtonne et al., 2016)	MFA + Markov chain + LCA	x			Food (cereals)
(Binder, 2007)	MFA + Social models			x	-
(Kytzia et al., 2004)	EE-MFA + IOA (Input - Output Analysis)	x	x		Food
(Sevigné-Itoiz et al., 2015)	MFA + CLCA	x			Waste paper recycling
(Widok et al., 2012)	MFA + DES + LCA	x	x		-
(Pirani & Arafat, 2016)	MFA + Water and Carbon footprint	x	x		Hospitality
(Giljum et al., 2014)	EW-MFA		x		All sectors worldwide

Table 1: Classification of the articles depending on the sustainable pillar studied with their methodology

It appears that generally, only environmental and / or economic models are combined with MFA. A future work could focus on combining social models with MFA. Different indicators have been used. Each of them belongs to one of the aspects of sustainability. Table 2 presents the classification of papers depending on the indicators used to evaluate the pillars of sustainability.

	Environmental	Economic	Social
(Courtonne et al., 2015)	Flows of cereals (Kilotons)	-	-
(Courtonne et al., 2016)	GHG emissions, energy use, land use, use of pesticides, blue water footprint	-	-

(Binder, 2007)	-	-	Review of different social models coupled with MFA
(Kytzia et al., 2004)	Primary energy consumption, land use	Turnover, Material Costs, other costs	-
(Sevigné-Itoiz et al., 2015)	GHG and CED	-	-
(Widok et al., 2012)	GHG, land use	-	-
(Pirani & Arafat, 2016)	FRESH number (Food waste Rating for Events vis-à-vis Sustainability in the Hospitality sector).	-	-
(Giljum et al., 2014)	-	DMC (Domestic Material Consumption)	-

Table 2: indicators used in the articles treating the three aspects of sustainability

Among the few papers identified, none of them evaluate all the aspect of sustainability. This may be a limitation of MFA and this challenge should be addressed and met.

4. CONCLUSIONS AND PERSPECTIVES

Knowing that different concepts exist to evaluate sustainable supply chains (Angelakoglou & Gaidajis, 2015), MFA can be combined with other methods and models to evaluate simultaneously the three pillars of sustainability. The objective of the current paper was to review the different papers that evaluate the flow of materials in a sustainable supply chain (SC).

The next step of our work is to extend our research to have a larger panel of methods and techniques to evaluate sustainability in SC. Then MFA will be applied to the fresh food products. Indeed, consumers have high expectations in terms of food security and food products demand for organic and local agriculture products is growing. The food industry meets the requirements necessary for sustainable development issues for the following reasons: first, because it is constantly under the close scrutiny of the public, then because environmental issues are regularly reported by government agencies and Non-Governmental Organizations, third, it answers to an essential need of human beings: to eat. In the US for example, agricultural activities contribute to greenhouse gas emissions up to 10 to 12% (Smith et al., 2007). Given the scope of work on the food industry, we decided to work specifically on fresh or perishable products. Special considerations are taken into account in order to preserve the freshness and quality of products, and require more limited delivery times, more controlled storage conditions, better quality of finished products and to minimize losses due to damage (Dabbene, Gay, & Sacco, 2008; Verdouw, Beulens, Trienekens, & Wolfert, 2010).

The final objective of this project is, based on the next review, to develop a model, which can evaluate simultaneously the three dimensions of sustainability in the fresh food supply chains.

5. REFERENCES

Amigun, B., Musango, J. K., & Stafford, W. (2011). Biofuels and sustainability in Africa. *Renewable and Sustainable Energy Reviews*, *15*(2), 1360–1372.

Angelakoglou, K., & Gaidajis, G. (2015). A review of methods contributing to the assessment of the environmental sustainability of industrial systems. *Journal of Cleaner Production*, *108*, *Part A*, 725–747.

Binder, C. R. (2007). From material flow analysis to material flow management Part I: social sciences modeling approaches coupled to MFA. *Journal of Cleaner Production*, *15*(17), 1596–1604.

Bringezu, S., & Moriguchi, Y. (2002). Material flow analysis. In R. U. Ayres & L. Ayres, *A handbook of industrial ecology* (pp. 79–90). Cheltenham, UK ; Northampton, MA: Edward Elgar Pub.

Brunner, P. H., & Rechberger, H. (2016). *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*. CRC Press.

Courtonne, J.-Y., Alapetite, J., Longaretti, P.-Y., Dupré, D., & Prados, E. (2015). Downscaling material flow analysis: The case of the cereal supply chain in France. *Ecological Economics*, *118*, 67–80.

Courtonne, J.-Y., Longaretti, P.-Y., Alapetite, J., & Dupré, D. (2016). Environmental Pressures Embodied in the French Cereals Supply Chain. *Journal of Industrial Ecology*, *20*(3), 423–434.

Dabbene, F., Gay, P., & Sacco, N. (2008). Optimisation of fresh-food supply chains in uncertain environments, Part I: Background and methodology. *Biosystems Engineering*, *99*(3), 348–359.

Duku, M. H., Gu, S., & Hagan, E. B. (2011). A comprehensive review of biomass resources and biofuels potential in Ghana. *Renewable and Sustainable Energy Reviews*, *15*(1), 404–415.

EPA. (2009). *Sustainable materials management: The road ahead (report and appendix – technical support document)*. Washington DC. Retrieved from https://www.epa.gov/sites/production/files/2015-08/documents/sustainable_materials_management_the_road_ahead.pdf

Eurostat. (2013). *Compilation guide, Economy Wide Material Flow Accounts (EW-MFA)*.

GIEC. (2013). *Résumé à l'intention des décideurs, Changements climatiques 2013 : Les éléments scientifiques. Contribution du Groupe de travail I au cinquième Rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat [sous la direction de Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex et P.M. Midgley]*. Cambridge, Royaume-Uni et New York (État de New York), États-Unis d'Amérique.: Cambridge University Press.

Giljum, S., Dittrich, M., Lieber, M., & Lutter, S. (2014). Global patterns of material flows and their socio-economic and environmental implications: a MFA study on all countries world-wide from 1980 to 2009. *Resources*, *3*(1), 319–339.

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., & Brunner, P. H. (2000). Material flow analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. *Local Environment*, *5*(3), 311–328.

Kuczenski, B., Geyer, R., Zink, T., & Henderson, A. (2014). Material flow analysis of lubricating oil use in California. *Resources, Conservation and Recycling*, *93*, 59–66.

Kytzia, S., Faist, M., & Baccini, P. (2004). Economically extended—MFA: a material flow approach for a better understanding of food production chain. *Journal of Cleaner Production*, *12*(8), 877–889.

Lavoisier, A.-L. (1789). *Traité élémentaire de chimie, présenté dans un ordre nouveau, et d'après les découvertes modernes ; Avec figures.* A Paris, chez Cuchet, libraire, rue & hôtel Serpente. M. DCC. LXXXIX. Sous le privilège de l'Académie des sciences & de la Société royale de médecine.

Pirani, S. I., & Arafat, H. A. (2016). Reduction of food waste generation in the hospitality industry. *Journal of Cleaner Production*, *132*, 129–145.

Sevigné-Itoiz, E., Gasol, C. M., Rieradevall, J., & Gabarrell, X. (2015). Methodology of supporting decision-making of waste management with material flow analysis (MFA) and consequential life cycle assessment (CLCA): case study of waste paper recycling. *Journal of Cleaner Production*, *105*, 253–262.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … Sirotenko, O. (2007). Agriculture. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)]* (pp. 497–540). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Van Dam, J. E., de Klerk-Engels, B., Struik, P. C., & Rabbinge, R. (2005). Securing renewable resource supplies for changing market demands in a bio-based economy. *Industrial Crops and Products*, *21*(1), 129–144.

Verdouw, C. N., Beulens, A. J. M., Trienekens, J. H., & Wolfert, J. (2010). Process modelling in demand-driven supply chains: A reference model for the fruit industry. *Computers and Electronics in Agriculture*, *73*(2), 174–187.

Widok, A. H., Schiemann, L., Jahr, P., & Wohlgemuth, V. (2012). Achieving sustainability through a combination of LCA and DES integrated in a simulation software for production processes. In *Simulation Conference (WSC), Proceedings of the 2012 Winter* (pp. 1–12). IEEE. Retrieved from

Wohlgemuth, V. (2005). *Komponentenbasierte Unterstützung von Methoden der Modellbildung und Simulation im Einsatzkontext des betrieblichen Umweltschutzes: Konzeption und prototypische Entwicklung eines Stoffstromsimulators zur Integration einer stoffstromorientierten Perspektive in die auftragsbezogene Simulationssicht*. Shaker.

APPENDIX

Nomenclature:

Acronym	**Meaning**
CED	Cumulative Energy Demand
CLCA	Consequential Life Cycle Assessment
DES	Discrete Event Simulation
EE-MFA	Economically Extended – MFA
EW-MFA	Economy Wide – MFA
GHG	Greenhouse Gas
IOA	Input - Output Analysis
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
SUT	Supply and Use Tables