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Material flow analysis for urban metabolism’s quantification in energy and digital transition: limits and perspectives

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The current global context has made sustainable development, sobriety and circular economy necessary objectives to fulfil. Local territories have their role to play in this transition: they need diagnosis of their material and energy consumption and resources to implement solutions and actions. Economy Wide Material Flow Analysis could be used as a decision-making tool by quantifying the material flows composing the urban metabolism of the territory. We identify nine limits that make Material Flow Analysis, and particularly the French reference method, difficult to use as a decision-making tool for small scale territories. A French territory has been used as a case study to experience the limits. The main one is data management: its collection, treatment and analysis are complex especially because of the diversity and multiplicity of data sources, the statistical secret and secret of business and the difficulty to access local scale and updated data. The digital transition with the development of data science and artificial intelligence has great potential to overtake this limitation.

* 1. Introduction

Sustainable development is an objective whose quest is essential in the current global context: territories face many challenges such as social and economic inequalities, global warming and the resource consumption that exceed the earth biocapacity and jeopardize the last accessible stocks of fossil resources.

Local scales are key actors in the implementation of sustainable development by carrying local action plans and policies: they have the capacity to define and organize their own ecological and energy transitions by taking their natural, economic, social or identity resources in hand (Buclet, 2015). In order to develop more sustainable practices, it appears necessary to move from linear production methods and mass consumption to a circular economy: it is a global approach aimed at a better management of resources to limit resources consumption and establish a loop of material flows.

The implementation of circular economy approaches, and a better management of resources is only possible with a flow diagnosis of the territory. The goal is to provide decision-making tools to guide territorial policies.

In this perspective, urban metabolism (UM) concept allows the study of all the flows circulating within a territory and links them with ecological and socio-technical processes. This concept stands out from common decision-making tools, based only on economic flows, by allowing material and energy accounting. Ittakes into consideration a material dimension and an immaterial dimension (social, cultural, political, economics flows).

The usual method to study the UM of a territory is material flow analysis (MFA) which is a quantification method. Barret et al. (2002) even consider MFA as a prerequisite for operationalizing the concept of sustainability.

In this context of ecological and energy transition, a digital transition is underway. Indeed, data became precious resources. But, with IoT technologies and social medias, their volume, complexity and size exceed the management capabilities of relational databases; consequently, new technologies have emerged such as artificial intelligence.

In this paper we present MFA concept, objectives, methods and the nine associated limits we identify through a literature review and a case study. Finally, we introduce the opportunities offered by the digital transition in order to make MFA a decision-making tool to support and guide the ecological and energy transitions.

* 1. MFA concept, objectives approaches and methods

Several types of MFA can be distinguished. First, economy-wide MFA (EW-MFA) that considers all the incoming and outgoing material flows (except for water and air) of an economy: all solid, gaseous and liquid materials (Eurostat, 2001). The purpose of EW-MFA is to quantify the exchange between a territorial system and its environment – natural and economic to (Ribon, 2020): understand resource consumption, identify flows at stake and potential, identify material resources, feed local action plans and political decisions, etc.

Second, the substance flow analysis (SFA) is a MFA focused on a chemical substance or product: it can be used to quantify pollution or to help the management of a resource. Finally, a MFA can focus on an industry or a value chain. It can be considered as a type of SFA or a fully-fledged MFA type.

Two different types of approaches can be identified to operate a MFA: top-down and bottom-up.

Top-down approaches allow to study a system from the outside: flows are quantified without having them linked to the process or activities they take part of. It is from the quantification that the characteristics of the system are deducted. These approaches are based on statistical data and are more suitable for EW-MFA. In Europe and in France, top-down approaches are the most known and used thanks to the method developed by Eurostat in 2001 (Eurostat, 2001) for EW-MFA at national level. The French General Commission for Sustainable Development (FGCSD) has adapted it for French local scales in 2014 (CGDD, 2014).

Unlike top-down approaches, bottom-up approaches allow flows quantifications starting from an analysis of the system and the processes, dynamics, activities that occur. They focus particularly on business activities because they are the main resources consumers of a territory. In this case, data can be hard to get: businesses could consider their material and energy flows information as strategic because linked to the company performance (Belaud et al., 2017). This difficulty increases with new regulations on business secrets.

* 1. MFA methodological limits illustrated by a French territory case study

Whatever the approach used, MFA methods have limitations which make using MFA as decision-making tool difficult. Nine limits can be identified from literature and practice, as discussed hereafter.

To experience and challenge these limits, a North French territory called “Pôle Métropolitain du Grand Amiénois” (PMGA) was chosen. The PMGA is composed of eight multi-municipality organisations for a total of 466 municipalities and 387 thousand inhabitants. An E2PM (material programming and planning study) has been launched for this territory in 2025 to establish a diagnosis using EW-MFA according to the FGCSD method.

* + 1. Exhaustivity

According to Buclet (2015), it is neither materially possible, nor relevant to try to be exhaustive when quantifying an UM. It is complex, even impossible, to quantify the flows exhaustively due to their multiplicity and diversity: some small flows (in terms of mass) can be forgotten during the MFA. Nevertheless, they can have a large impact on the system: for example, they can cause an important pollution. So, in which extent is it relevant to be exhaustive? The use of critical indexes per flow to balance their mass could help to solve this challenge.

During the PMGA study, we quantified more than sixty main flows. One of the brakes to exhaustivity is also data and its existence but this point will be discussed in the 3.8.

* + 1. Water and energy flows

According to the Eurostat method (Eurostat, 2001) and French method (CGDD, 2014), two major and at stake flows are excluded from the analysis: water flows and flows of non-quantifiable energies in mass.

First, water flows: their rough size, largely higher than all the other flows, would hide them all (CGDD, 2014). The study of water flows is done generally with dedicated methods, given the complexity of water life cycle and the lack of data about non-drinkable water. The PMGA territory didn’t identify water flows as priority stake because it is not in water stress. Nevertheless, it could be more and more exposed to drought as it has been in the summer 2022. We limited our study to taxed water extractions (volume higher than 10 000m3) and to rainfall. We decided to exclude natural water flows as for example rivers or evapotranspiration. The data were presented in a dedicated diagram. It turns out that the territory was very interested in this subject: the study allowed us to outline the rainwater salvage potential that could be used for irrigation.

Second, regarding energy flows, only those quantifiable in mass are considered; for example, fossil fuel or wood that will be used as combustible. Thereby, electricity flows produced, imported, consumed or exported by the system are excluded. However, energy is a relevant measure of the ecological print of a system.

In this perspective, Kim (2013) focused on energy flows (primary and secondary sources) that supply a territory. She quantifies, relying on MFA, in mass and then in energy value, all the materials that compete for various energy, nutritional and technical uses. To overcome this limit, electrical energy can also be converted into an equivalent “energic vector” thanks to conversions factors (Barret et al., 2002). In the same way, Lee et al. (2016) convert energy flows into megatons of oil equivalent. Energy flows of PMGA have also been quantified by using territorial data: final energy consumed, and renewable energy produced by the territory in GWh. As for water, the energy flows were represented on a dedicated diagram: it allowed to compare the PMGA to other territories in terms of energy autonomy and renewable energy consumption.

In the current planetary and ecological context, water and energy flows are important stakes and territories ask more and more to integrate them to MFA: it can allow a better understanding of their metabolism thanks to a more global vision.

* + 1. Material and insubstantial flows

Whatever the method used, MFA can be considered reductive because the territory is only considered as an exchange of matter between flows and stock. Indeed, some economic, social or cultural questions seem hardly approachable only through the prism of matter and energy (Ribon, 2020). The integration of other aspects into UM analysis seems necessary to better understand the relationships between the socio-economic system and the individual and collective way in which materials, goods and energy are produced and consumed within territories (Dijst et al., 2018).

Firstly, social and economic dimensions can be added to UM such as the interaction system between territorial stakeholders to understand flows governance; economic flows; or unsubstantial flows such as cultural, politics or informative aspects. Nevertheless, it is interesting to notice that unsubstantial flows have an impact on material flows: there is still a "mass" logic in considering insubstantial social and economic effects.

Secondly, a territorial capacity analysis could help quantify the capacity of the biosphere to support demand and to assimilate the territory's discharges: it could help assess the sustainability of the territory. Moreover, a resource risk assessment could be interesting to evaluate. The companies which consume most of a flow or employ the most inhabitants of the territory could be identified and linked to the flows that could be at stake in case of crisis. Some of PMGA stakeholders have shown interest in this notion to build their material strategy and increase their autonomy.

Thirdly, land stock could be quantified because it is a resource at stake with pollution and artificialization.

Fourthly, the qualification of the flows could be relevant to evaluate, for example, the recyclable part.

Finally, other dimensions could be integrated by combining MFA with other methods such as life cycle analysis or input-output analysis.

It is nevertheless important to emphasize that adding dimensions to the MFA leads to a complexity in a study that was already complex due to the multiplicity of flows and material stocks transiting and existing in a territory. And, in order to help decision-making, complexity is not always necessarily desired.

* + 1. Back box vision

The top-down method allows to study the territory only as a “black box” because it omits all the flows and elements present within the study system as well as the processes that occur there. However, the latter should not be ignored since they allow a better understanding of the territory. This limit marks a break with the concept of metabolism itself since there is no understanding of exchanges within the system.

Many researchers have tried to overtake this limit using SFA for specific flows or with modelling the territory, whatever it is a global (Cui, 2022), by value chain (Courtonne, 2016) or subsystem approach (Buclet, 2015).

This black box vision is one of the limitations of top-down methods. While for some flows, the top-down method is enough – for example, importations and exportations or agriculture production -, for others it is necessary to understand what occurs inside the black box. For example: data about waste production is not sufficient to understand the territorial waste metabolism. For those flows, a bottom-up approach is needed in addition to the top-down one. For the PMGA, we studied waste flows for each multi-municipality organisations and then combined them to have the result for the global territory. It allowed us, for example, to quantify the waste burying, the recycling, and the exchanges between the eight multi-municipality organisations.

As we experimented for this case study, going in the black box and representing all the flows lead to a complex representation even if it is for only one type of flows. It provides proof of the difficulty that would be of representing all the flows considered in a top-down EW-MFA.

* + 1. Territory stock

Only the net addition to the stock is calculated when doing a MFA, particularly with the French top-down method (CGDD, 2014). However, stock is a central element of the territory: it is the link between incoming and outgoing flows (Augiseau, 2017). The stock can also be a mine of resources. Its quantification has a real utility for the actors in the management of the allocation, use and management of resources and waste, but it is a complex and time-consuming exercise needing precise territorial data (Fishman et al., 2014).

With the goal of quantifying a territorial stock, many approaches exist. For example, Augiseau (2017) developed a method to quantify material stock, composed of construction and public works, road and railway network and pipe network, in a French region; and Fishmann et al. (2014) have adopted a more general method to quantify the stock of a country. This aspect wasn’t studied for the PMGA, but it could be interesting to quantify the stock for some key sectors such as building material stock.

* + 1. Temporal representation

With current methods, the territory is analyzed at a given moment and not continuously. However, the territorial system is subject to continuous changes and flows evolve with time especially due to major infrastructure works, demographic evolutions or changes in the economy. The evolution speed can depend on the type of flow.

UM could be represented in time in three ways: dynamic, historical and prospective vision. Firstly, dynamic vision could allow for more accurate management by allowing a better understanding of flows evolution under the impact of political decisions or changes on the territory. Particularly, the development of digital models could allow territories to follow their UM evolution (Stephan, 2022). Secondly, historical vision helps complete the UM analysis to understand previous socio-economic transitions and their historical founding principles to better anticipate future transitions. The work of Fishmann et al. (2014) can make links between historical and prospective vision: they worked on materials stocks at a country level from 1930 to 2005 in order to define possible evolution scenarios up to 2050. Thirdly, the potential of the use of prospective vision to study UM reaches consensus in the scientific community (Wang et al., 2023).

In PMGA case study, based on the EW-MFA diagnosis, prospectives scenarios for 2050 were proposed to establish a strategy and action plan. This case shows the interest and potential of a prospective vision on material flows for territories.

* + 1. Spatial representation

By using current methods, it is generally not possible to visualize flows spatially. However, being able to do so would make it possible to better identify their spatial distribution in order to implement better geo-social management (Fishmann et al., 2014) and take into account geographical inequalities. Nevertheless, flows spatial representation is a technical and conceptual challenge because the spatial structure of a flow is characterized by many supply and consumption areas. Heat maps could be a good solution to represent places with the most and less flow density.

* + 1. Data

Data are an integral condition for the realization of MFA: without data, there is therefore no MFA, only a qualitative analysis. The majority of MFA studies point out this limitation. Indeed, to carry out a MFA study representative of the functioning of the territory, significant work on the data is necessary: collection and processing. Moreover, overcoming all the other limits highlighted in this paper can only be done if data are available.

The first challenge concerns data collection of updated data at a precise spatial and temporal scale. Firstly, while at national level many data sets are available, it is not the same at local scale and smaller it is, harder it is to find or access local data. Indeed, with the statistical secret and the business secret law, more and more data are no longer available for smaller scales. In France, while with Open Data trend we should observe more and more data sets useful for MFA, paradoxically, data richness has decreased, as discussed by Buclet (2015). Secondly, the same analysis can be made about temporal scale and the access to dynamic evolution of data. In general, the time needed to develop local and quality data is often not compatible with the timing of projects and policy development processes (Longato et al, 2019). The data collection for the PMGA reflects this difficulty. More than 40 data sources have been used providing more than 60 data sets. Many different data formats have been used, mostly pdf, csv and xlsx. For some flows, such as farming effluents or economic activity wastes, there is no data available: specific assessment methods need to be developed. Finaly, some of the data required an admission to the French Commission of Statistical Secret. The PMGA is a small-scale territory; few data are available at this scale: some estimations have been made by using population ratios for example. Regarding temporal scale, the more recent data available have been used and, when possible, a mean has been used on the three last years in order to have reliable data.

The second challenge is qualifying data. With the multiplicity of data sources and producers, this question is central when making a MFA (Dijst et al., 2018). Indeed, if MFA studies need to help manage territorial flow and resources, it is necessary to find and use good quality data, that is to say, in particular, true, consistent, complete and reliable data. For the PMGA, we faced many different difficulties linked to data quality: lack of metadata preventing the understanding of data, lack of uniformization / updating of municipalities names or errors on the data itself.

The third challenge is linked to data processing: this step is complexified by the diversity and multiplicity of data sources necessary for a MFA. Indeed, the number and variety of data needed to be managed can also lead to human errors during their treatment. Difficulty can also be found in the choice and use of data managing and analysing tools. For the PMGA, many challenges have been encountered such as the treatment of pdf data whatever they are text or table, difficulties linked to nomenclature understanding and correlation between different data sets, data set and the method itself or to the trap of double counting some flows.

* + 1. MFA as decision-making tool

The implementation of MFA sometimes lacks a link with the implementation of actions and policies (Wang et al, 2023): they are often used more for educational purposes than for real decision-making purposes.

One of the challenges is to make the MFA understandable and workable for territorial’s stakeholders (Ribon, 2020).

Indicators, such as the ones proposed in the French MFA method (CGDD, 2014), could also help assess territorial policies and comparing territories between them: for example, direct material input/output, total domestic output, total material consumption.

Although the study for PMGA is not finished yet, the EW-MFA realized for this territory has been used to detect and choose sectors and flows at stake and to analyze potentials and flows that can be redirected into the territorial economy. Indicators such as ratio per inhabitant to compare the PMGA to other territories (region and France) or the total consumption of the territory (imports + production – exports) have been used. The MFA analysis will help build the 2050 prospective scenarios and feed the strategy and action plan.

* 1. Future work and challenges

In order to develop a finer modelling of a small-scale territory, the next goals are:

* To define which water flows need to / can be quantified and how their integration in the global representation can be made.
* To develop a method to integrate energy flows (particularly electrical flows) to the general representation without double counting material flows used to produce energy such as oil or natural gas that are, partly, already taken in consideration in importations flows.
* To develop methods to estimate flows for which there is no satisfying data available.

Moreover, as presented before, many researchers are focusing on one or several of those limits of MFA for urban metabolism’s quantification in energy and digital transition. However, all research on this topic comes up against the same constraint: the difficulty of extracting, collecting and cleaning all the desired and needed data. For decades, data on material stocks and flows have been compiled and published individually in diverse and often inconsistent formats that make it difficult to synthesize, exploit and improve (Myers et al., 2019).

Big data supports sustainability management at various levels (Belaud et al., 2019). Indeed, approaching MFA from the perspective of (big-)data management and processing could allow to extend the methodological practice focused on UM and territories in general. In this context, it would seem interesting in particular to question the opportunities offered by data sciences and artificial intelligence to produce, collect, clean, reconcile, explore, represent and analyze data. Particularly, machine learning could help taking into account the data diversity and its heterogeneous sources (Prioux et al., 2022). For example, artificial intelligence could be used to extract useful data from pdf documents, to produce data visualisations or to make a first analysis of the territory context to assist the experts. The automatization of a part of data collection and treatment thanks to a tool could help gain time to focus more on the analysis.

However, the use of data science and artificial intelligence need data to be used. Many consider that the responsibility for producing and publishing good quality data could be mostly incumbent upon territories. In France, in 2023, a growth of concern about territorial data has been noticed: 97% of local authorities agree to the fact that data mastery is necessary and 65% of them have launched a data project in the last two years (Observatoire Datapublica, 2024). But, for many reasons such as budget restriction or the statistical secret law, it is still hard to find good quality data for small territorial scales. In this context, the use of new data sources could be considered: for example, data from geographical information system and all the data from remote sensing, particularly satellite data (Dijst et al., 2018).

The digital transition and the appearance of new technologies could help transform MFA and UM studies into real decision-making tools by overtaking their actuals limits. In this way, it could help policymakers to better manage ecological and energetic transitions.

* 1. Conclusion

The paper reviews the MFA concept and its limits for urban metabolism studies: the exhaustivity and criticality of flows query; the exclusion of water, energy flows and other material and insubstantial dimensions; the black box; the lack of stock quantification; spatial and temporal representation; data; and the lack of link between MFA and policies and actions implementations. These limits have been tested by using the French MFA method for a French territory. Digital transition, particularly data science and artificial intelligence, can enhance data collection, production, cleaning, reconciliation, exploration, and analyzing required by MFA. Nowadays, there is very little that contributes to the use of data science and artificial intelligence for research on urban metabolism and material flow analysis: this track remains to be explored, and important work needs to be done.

In this way, digital transition can support urban metabolism as a tool for ecological and energetical transition.

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