INTEGRATION OF AN URBAN METABOLISM FRAMEWORK WITH GEOGRAPHIC INFORMATION SYSTEM SOFTWARE

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INTEGRATION OF AN URBAN METABOLISM FRAMEWORK WITH GEOGRAPHIC INFORMATION SYSTEM SOFTWARE

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Introduction

The current utilization of maps and Geographical Information System (GIS) software to display the results from Urban Metabolism (UM) studies is still limited and being developed. According to Benavides (2017), the utilization of GIS in the UM analysis is still not widespread but represents an alternative that continues in development.

The purpose of this document is to analyze different UM frameworks and identify which are the most adequate to be used in combination with GIS software to display the results of its analysis and provide a visual aid to communicate better these results to policy-makers and stakeholders.

To start, it has been defined a list of features that would be desirable to have as an outcome as well as “what” and “how” to display. For this matter, on the one hand a list of UM tools taken from Benavides (2017) in addition to current approaches utilized in some European cities have been assessed. On the other hand, various GIS tools and software have been assessed. From these two assessments a short-list of which UM frameworks and which software tools could be used was created.

Subsequently, the possible combinations of UM frameworks and software tools have been analyzed by means of a matrix and a recommendation is given in terms of the adaptability, the time requirements and the costs of software licenses and additional features.

Figure 1 shows the steps previously described process to provide a final recommendation.

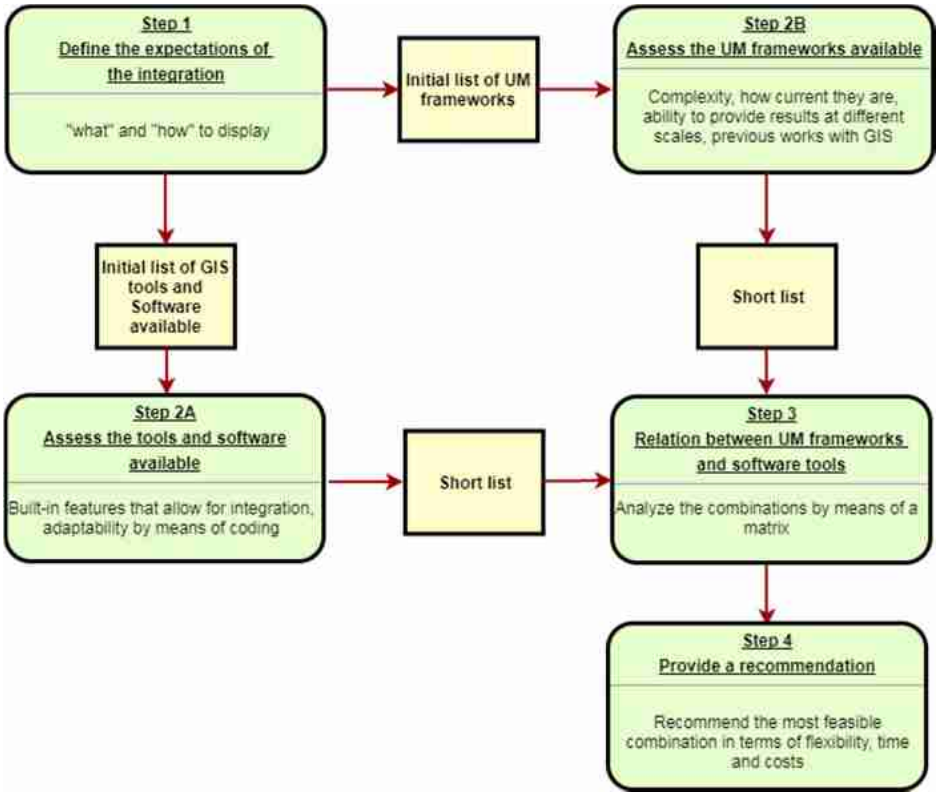

Figure 1. Steps followed for recommendation.
Source: own elaboration

Step 1: Expectations of the integration between UM and GIS. What and how could be possibly represented by GIS related to UM?

Existing examples

In order to have a view of what outcomes can be expected and how it has been developed, some existing representation of UM analysis with GIS were reviewed. From this literature review only a few cases were found where urban metabolism studies are somehow represented using GIS.

One first example considers the cases of Rotterdam, Brussels, Antwerp and Albania, performed in a collaboration of different institutions from the Netherlands, including the TU Delft, .FABRIC design office and the PBL Netherlands Environmental Assessment Agency, in scope of the International Architecture Biennale Rotterdam (IABR). Whether for all these studies the same approach to urban metabolism was followed, is not clear. Nevertheless, at least for the case of Rotterdam, the Material Flow Analysis (MFA) and Life Cycle Analysis (LCA) were used (Tillie, 2014). Unfortunately, the specific MFA method used is not described.

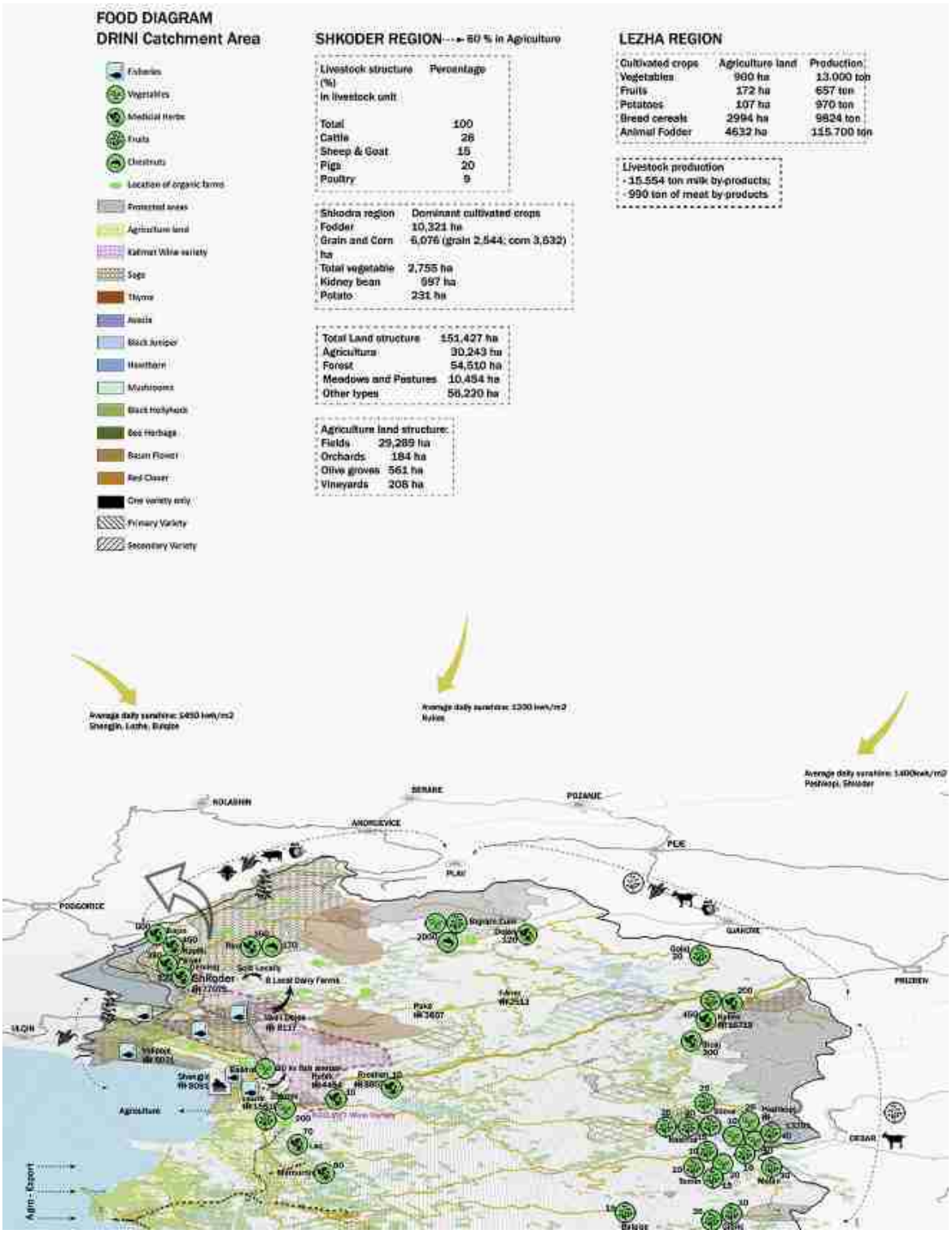

Figure 2. Urban Metabolism of Albania (Food).
Source: https://www.behance.net/gallery/40339307/The-Metabolism-of-Albania

In another example presented by Giampietro et al. (2013), the MuSIEASEM framework is used to present the suitable land for cultivation of different types of crops in Mauritius.

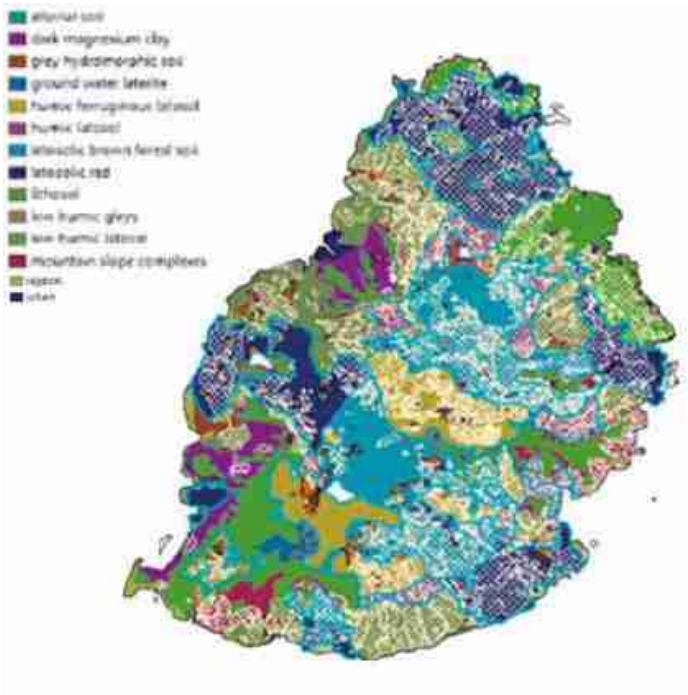

Figure 3. Information for the suitable land for the cultivation of a different crop mix in Mauritius.
Source: Giampietro et al. (2013)

Additionally, current efforts are being made by the IASTE research group at the Institute of Environmental Sciences and Technologies (ICTA) from the Autonomous University of Barcelona to develop more GIS oriented results from its MuSIASEM framework (Velazco-Fernández, Raúl, personal communication, March 3, 2019). However, there are not many representations yet and the existing ones are mostly limited to show geographical location of resources. Some of the publications reviewed are: Pérez-Sánchez et al. (2019), Giampietro et al. (2001), Giampietro et al. (2013), González-López and Giampietro (2017) and Serrano Tovar (2014).

The third example is a more commercial product called Suscity. Nevertheless, some publications are available on scientific sources in regards of the methodologies and approaches followed (Costa and Santos (2018), Costa and Santos (2017), Evans and Steadman (2003) , Gomes et al. (2018), Iria et al. (2017), Monteiro et al. (2018), Monteiro et al. (2017) and Panão and Brito (2018)).

SuScity is developed by the Center for Innovation, Technology and Policy Research from Portugal, where a first approximation (http://arcst.tagus.ist.utl.pt/UMSC/LMA/) intended to display on Portugal's map the different resources' consumption, water supply and population. This approach seems to have been succeeded by a much larger project with a consortium that includes public and private institutions in order to model urban systems, using Lisbon as a case study. This project comprises a set of six work packages, from which the first includes an Urban Metabolism Simulator (UMS) (http://groups.ist.utl.pt/suscity-project/scientific-methodology/work-

package-1/). This project focuses on a bottom-up approach to analyze the metabolism, starting at the building level and then expanding to the neighborhood and city level. This characterization is based on Material Flow Analysis (MFA) and Life Cycle Assessment (LCA). The general approach of the project is based on the collection and processing of "big data" at the urban level (http://groups.ist.utl.pt/suscity-project/home/). In this case, the requirements for data acquisition and processing, together with their impacts should not be underestimated.

Another project that introduces the utilization of spatial analysis for UM is the REPAiR project (REsource Management in Peri-urban AReas). This project integrates models from the environmental, economic and geographic sciences with design and spatial planning methods on a software and process level, which has been called the Geodesign Decision Support Environment (GDSE). Its main objective is to demonstrate the feasibility of utilizing such a process for decision-making on water and resource management considering sustainable strategies (http://h2020repair.eu/).

REPAiR is based on the Extended UM (EUM) approach in combination with LCA to study the waste and resource management focusing on space-specific challenges. This is performed in context of geodesign: "an integrated process informed by environmental sustainability appraisal, which includes project conceptualization, analysis, projection and forecasting, diagnosis, alternative design, impact simulation and assessment, and which involves a number of technical, political and social actors in collaborative decision-making'" (Campagna, 2014). The specific method for UM analysis used is the project specific and newly introduced "Activity-based Spatial Material Flow Analysis" (AS-MFA) (Geldermans et al., 2017).

This project is still in development and the software tool, which is open-source, is available in a beta version. Access to the current versions of the software tool and the installation manual can be found at: https://github.com/MaxBo/REPAiR-Web.

Expectations from the integration

At first glimpse, GIS could be utilized to show the localization of resources and the products generated with their flows, typically starting at a regional level with the possibility to zoom in to a local level or even building-specific if the data is available. The resources that could be included are water, food and energy. In addition, the different types of waste should be involved.

Ideally, the flows in the maps should utilize distributive lines, in which the arrows have a different thickness depending on their numerical value. Furthermore, Sankey diagrams for each resource type in the map, and ideally at different scales (local to regional), could be available as a feature for a more complete understanding of the flows. These Sankey diagrams could be shown when selecting the specific resource's distributive line on the map.

Figure 4 shows how a Sankey diagram for the food flow of the UM in Albania looks like.

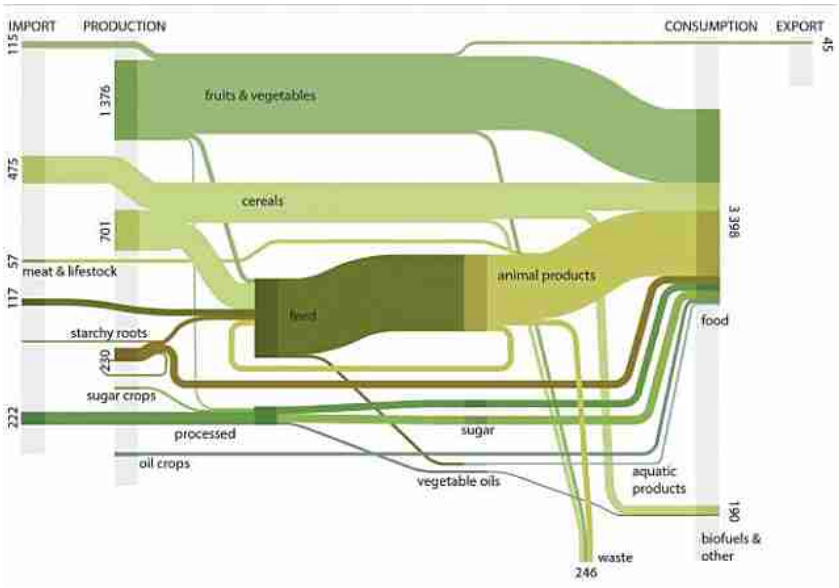

Figure 4. Sankey diagram for the food flow in Albania's urban metabolism.
Source: https://www.behance.net/gallery/40339307/The-Metabolism-of-Albania

Step 2: Assessment of software tools and UM frameworks

Step 2A: Assess the software tools available

A variety of GIS tools are available, open-source as well as license based. Two of the most common tools from each category are QGIS and ArcGIS Pro (or ArcMap), respectively. Considering the expectations described in Section *Step 2A: Assess the software tools available*, the features available in these software tools for the representation of flows with distributive lines on maps are shown in Table 1. These features can be useful to approximate the visualization on the map to a Sankey diagram. Nevertheless, a further display of a complete Sankey diagram for a selected resource flow could be developed by means of coding with Python.

	ArcGIS	QGIS
Features	**Distributive Flow Lines tool** https://www.arcgis.com/home/item.html?id=04fa6ed8746b451892f339011aaf989d https://community.esri.com/groups/applications-prototype-lab/blog/2019/03/05/distributive-flow-maps-for-pro	**Delaunay Lines with AequilibraE plugin** http://aequilibrae.com/ https://www.siliconcreek.net/transportation/building-better-desire-lines-in-qgis-using-aequilibrae
		Stocked bandwidths with AequilibraE plugin https://www.youtube.com/watch?v=u-8S4F0LdJU
		Flowmapper https://gogeomatics.ca/mapping-migration-flows-with-qgis-flowmapper-plugin/ https://anitagraser.com/2016/12/18/details-of-good-flow-maps/

Table 1. GIS software tools and features.
Source: own elaboration

The Distributive Flow Lines tool is a plugin available in the ArcGIS repository and has been recently updated in March 2019. It is based on raster due to an improved processing time and control over the lines. A complete explanation about the basis and utilization of this tool can be found in the web pages listed in **Table 1**. The distributive lines can be useful since they illustrate the flow of one source to several destinations with a joint line that forks to the different destinations instead of showing individual lines for each flow. In order to show line widths in correlation with the numerical values of the flows, further manipulation of the tool settings will be required. However, in this representation is not possible to determine the line width as function of the flow value. This is compensated by the possibility of showing the numerical values of the flows as labels on the lines. An example can be seen in **Figure 5**.

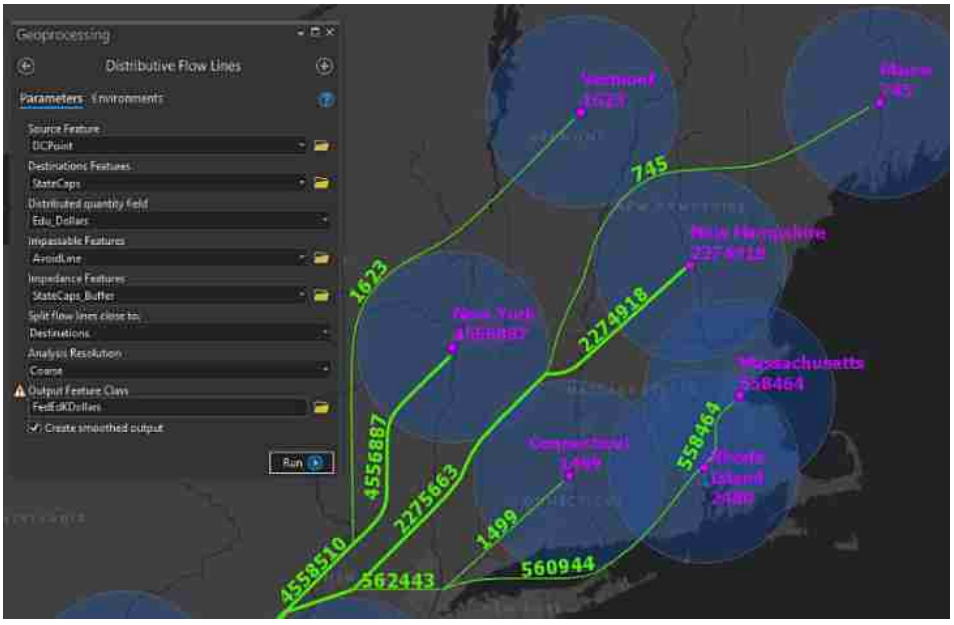

Figure 5. Distributive Flow Lines example in ArcGIS.
Source: https://community.esri.com/groups/applications-prototype-lab/blog/2019/03/05/distributive-flow-maps-for-pro

With QGIS, the open-source alternative, it is possible to represent flows with the AequilibraE plugin, which is a transportation modeling toolbox. Two options to represent these flows are “Delaunay lines” and “stacked bandwidths”. Both are approaches to transport analysis that might need further study to corroborate their validity in the analysis of material flows. At first sight it seems a very straightforward approach, since the data is retrieved from a database and it is used to draw a representation on a map without numerical manipulation or “traffic” calculations.

The Delaunay lines are based on the initial approach of simple desire lines but they use Delaunay triangulation[1] and the method has already been used for a representation of material flows. This is the case of the “Pavilion of Brazil at the Biennale Architettura 2018” in Venice, Italy[2]. This map, shown in **Figure 6** was generated with QGIS and the AequilibraE tool by its developer Pedro Camargo. The high definition image is available at http://www.xl-optim.com/site/more-delaunay-lines/Material_Flow.jpg.

The example cited describes the material flows for Brazil’s import and export of commodities. Despite this particular example is still difficult to appreciate in small size, it is still possible to realize the potential of the tool to represent the results of UM analysis.

[1] Are widely used in scientific computing and define triangles with two important characteristics: well-shaped triangles and the nearest-neighbor relation. “For a set of points in 2-D, a Delaunay triangulation of these points ensures the circumcircle associated with each triangle contains no other point in its interior.” (https://www.mathworks.com/help/matlab/math/delaunay-triangulation.html)

[2] The method used for the calculation of the material flows is actually unknown since the data was recollected existing sources.

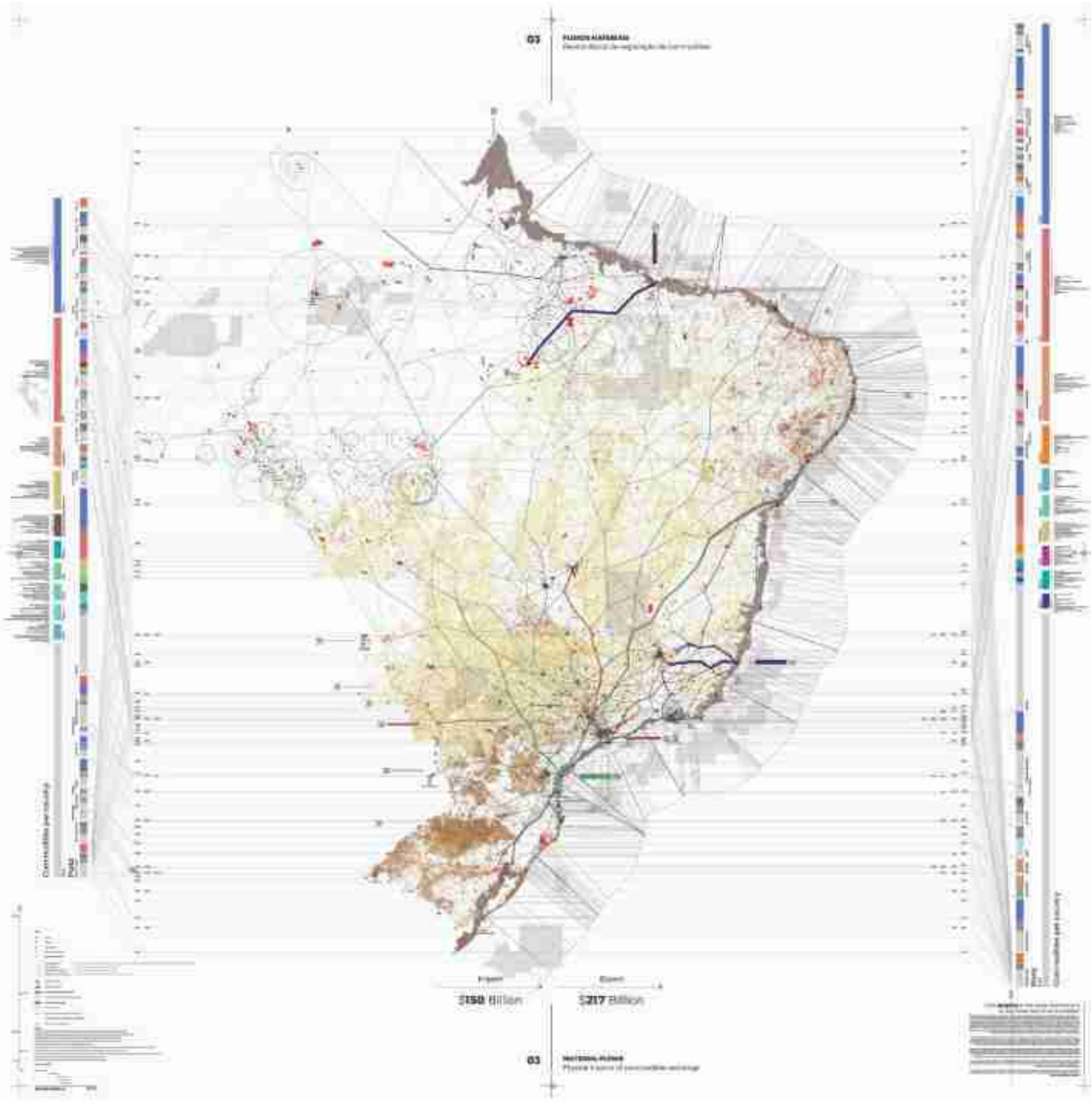

Figure 6. Material flow of import/export of commodities in Brazil
Source: http://www.xl-optim.com/more-delaunay-lines/

In addition to delaunay lines, in AequilibraE there is the option of generating stacked bandwidths. These are a visual resource in order to vary the line thickness as a function of the flow values in the database. A combination of desire lines with stacked bandwidths might result very convenient for the UM analysis. Since this tool is developed for traffic analysis, the examples available depict transportation networks with thickness and colors that vary according to the total flow and the ratio volume/capacity respectively.

Figure 7. Stacked bandwidths with AequilibraE.
Source: http://www.xl-optim.com/stacked-bandwidths/

The third tool identified for QGIS is the FlowMapper Plugin, which also shows some convenient features for the UM analysis, especially if further tuned with additional coding as shown in Anita Graser's blog (link in **Table 1**). The improvements considered with the additional coding are based on the recommendations for 'origin to destination flow maps' from Bernhard et al. (2018). An example of the Canadian migration can be seen in **Figure 8**. With this tool it is possible to represent flows avoiding overlapping, to scale width according to flow value and other aesthetic considerations. Nevertheless, the specific trajectory of flows will not reflect the actual path (similar to Delaunay lines, the trace is generated only on an origin-destination base).

Figure 8. Interprovincial migration in Canada 2014/2015.
Source: https://gogeomatics.ca/mapping-migration-flows-with-qgis-flowmapper-plugin/

In case a detailed trajectory of the flows generated from the UM analysis is known and it is depicted in the map, it will be possible to obtain better results based on the utilization of stacked bandwidths. If that is not the case, whether Flowmaps or Delaunay lines can be used, and the trajectory obtained will not represent that of the flow in reality and will only have illustrative value.

Table 2 illustrates the possible approaches with AequilibraE and Flowmapper depending on the availability of specific flow trajectories as an output from the UM analysis:

Is the real trajectory of flows an output of the UM analysis?			
Yes		No	
Flowmapper	**AequilibraE**	**Flowmapper**	**AequilibraE**
This benefit is lost since the tool only works with source/ destination nodes	"Stacked bandwidths" could take a DB with the lines generated as output from the UM analysis and represent them (in thickness and color) as a function of the total flow and the volume/capacity ratio	It will generate curved lines between source and destination nodes. With additional (available) coding, it is possible to display thickness as a function of the flow value, to show flow direction with arrows and other aesthethic considerations	"Delaunay lines" could be used to connect source and destination nodes using the delaunay triagles principle, therefore in an efficient, ordered manner. Later, these lines could be treated as "stacked bandwidths" for better representation

Table 2. Plugin functionality depending on real flow trajectory availability.
Source: own elaboration

Short list of software tools

From the two GIS tools presented, it is considered that QGIS offers more ready-to use options and with results more in line with the expectations. First, as open-source software, there are no costs involved in licensing. Second, the distributive flow lines tool found for ArcGIS presents limitations in regards to presenting the flows' thickness as a variable of their value and ready-to-use code to further tune its results.

In the case of QGIS, it is considered that the AequilibraE and Flowmapper pluggings offer enough flexibility for the representation of flows thanks to available ready-to-use code for customization and community/developed support. Nevertheless, for the case of ArcGIS, there is always the possibility of developing Python code from scratch to overcome the existing limitations. For these reasons, it is considered that both GIS tools could be further analyzed.

Step 2B: Assess the UM frameworks available

A list of options for UM analysis (based on the UM Measuring Tools section presented by Benavides (2017)) has been analyzed on **Table 3**. In this table, each tool or framework is appraised in regards of some criteria considered important for the representation of its results in a GIS software tool and its significance over time.

Tool	Characteristics	Usefulness in present times	Considers geographic distribution? (GIS integration)	Potential to be used in developing regions	Is it current?	Selected bibliography & Case studies
Black box accounting	Provides a general overview but lacks of information inside the box and of social factors. Flows do not give information about internal process.	As first approximation	No	It could be easily used due to its simplicity	Not as a single method but part of a larger analysis	Ngo, N. S., & Pataki, D. E. (2008). The energy and mass balance of Los Angeles County. Urban Ecosystems, 11(2), 121-139. Delgado, G. C., Chávez, C. C., & Juárez, P. R. (2012). Cambio climático y el metabolismo urbano de las megaurbes latinoamericanas. Habitat sustentable, 2-25.
EIO-PIOT	It is an accounting method primarily used in Economics. The physical component illustrates the physical flows of the materials. They have been extended to show the environmental impacts related to economic and material flow.	Used by most countries to show national accounting. One of the official methods in the EU	Sector, local, national levels wise. Might be difficult do down-scale available data	Data scaling could be prohibitive.	Yes	Pincetl, S., Bunje, P., & Holmes, T. (2012). An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. Landscape and urban planning, 107(3), 193-202. https://metabolismofcities.org/tags/65/physical-input-output-tables-piot-input-output-assessment-ioa Ferrão, P., & Fernández, J. E. (2013). Sustainable urban metabolism. MIT press.
EUROSTAT	Economy-wide material flow analysis (EW-MFA). It has global relevance and is a robust method. It is one of the three official methods for environmental accounting and reporting in the EU since the 1990s. It uses many indicators based on European standards. It is designed originally for national level, so it needs adaptations to work for smaller scales.	One of the official methods in the EU.	Yes, if adapted.	Data format may not follow the standard but adaption might be possible	Yes	Hinterberger, F., Giljum, S., & Hammer, M. (2003). Material flow accounting and analysis (MFA). A valuable tool for analyses of nature-society interrelationships. SERI Background Paper, (2). Barles, S. (2009). Urban metabolism of Paris and its region. Journal of industrial ecology, 13(6), 898-913. Niza, S., Rosado, L., & Ferrao, P. (2009). Urban metabolism: methodological advances in urban material flow accounting based on the Lisbon case study. Journal of Industrial Ecology, 13(3), 384-405. Voskamp, I. M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J. P., & Rijnaarts, H. H. (2017). Enhanced performance of the Eurostat method for comprehensive assessment of urban metabolism: a material flow analysis of Amsterdam. Journal of

Tool	Characteristics	Usefulness in present times	Considers geographic distribution? (GIS integration)	Potential to be used in developing regions	Is it current?	Selected bibliography & Case studies
						Industrial Ecology, 21(4), 887-902. https://metabolismofcities.org/publications/results?search%5B%5D=7
Urban Metabolism Analyst (UMAn)	It can be an option to bridge the different methods adopted in the EU. It can use additional datasets to the EUROSTAT, which allows for scale adaption. Includes additional data bases related to lifecycle. Material consumption can be traced and flows can be determined. Intends to provide improved understanding of origin/destination of flows.	As a complement and extended use of the EU methods.	Yes, depending on the scale of the data	Data format may not follow the standard but adaption is possible	Yes	Rosado, L., Niza, S., & Ferrão, P. (2014). A material flow accounting case study of the Lisbon metropolitan area using the urban metabolism analyst model. *Journal of Industrial Ecology*, 18(1), 84-101.
Extended Urban Metabolism (EUM)	It acknowledges more complexity and considers context characteristics like urban patterns, policies and lifestyle. This is done by including indicators for environmental quality, urban drivers and urban patterns. The availability of data remains as a concern.	Thought for city-size analysis	Yes. Data sources might be directly in a Geo-based fashion (in different scales)	Data format may not follow the standard but adaption might be possible	Yes	Minx, J. C., Creutzig, F., Medinger, V., & Ziegler, T. (2011). Developing a pragmatic approach to assess urban metabolism in Europe: A report to the European Environment Agency.
Abbreviated urban metabolism (AUM)	Utilizes information from 28 indicators that are part of standard GHG accounting. The granularity of internal flows depends on the data available. The model does not analyze differentiated access to resources within city space. The method is simple, flexible and is based on a minimum set of data. Does not provide a deep understanding of the metabolism but only a general	Standardized by the World Bank and applied for several cases the largest cities of South America.	None of the case studies performed show representations on maps. Data is usually not granular enough.	It has been applied already	Yes	Hoornweg, D. A., Campillo, G., Linders, D., Saldivar-Sali, A. N., & Sugar, L. (2012, October). Mainstreaming urban metabolism: advances and challenges in city participation. In Sixth Urban Research and Knowledge Symposium (Vol. 2012).

Tool	Characteristics	Usefulness in present times	Considers geographic distribution? (GIS integration)	Potential to be used in developing regions	Is it current?	Selected bibliography & Case studies
	view.					
Baccini-Rechberger-Brunner method (MFA)	Is based on the idea that basic human activieties shape the societal metabolism. These are grouped into categories: "*to nourish*", "*to reside & work*", "*to transport & communicate*". Flows are established after the relevant activities are defined. One problem could be the granularity of the data required. However, if available it provides a deep understanding of the urban region studied.	Can provide granularity and its expandable on its 4 categories. Can provide from broad understanding of the general metabolism of a society/ city to a more specific scale.	Yes, depends on the scale of the data.	Offers the possibility of general application	Yes	Baccini, P., & Brunner, P. H. (2012). Metabolism of the anthroposphere: analysis, evaluation, design. MIT Press. Baccini, P. (1996). Understanding regional metabolism for a sustainable development of urban systems. Environmental science and pollution research, 3(2), 108-111. Barles, S. (2009). Urban metabolism of Paris and its region. Journal of industrial ecology, 13(6), 898-913.
Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)	It intends to capture the metabolic processes with a high complexity. Analyzes the system at multiple dimensions and scales. Has a solid theoretical background based on Georgescu Roegen's flow-fund bioeconomic analysis, thermodynamics based on the work of the Odum brothers, and on complex system theory. It uses empirical work to correct the model iteratively. It is based on determined flows: water, food, etc; fund elements (which consume these flows) and a flow/fund ratio. It contains a hierachical structure. Therefore considers different scales. It can provide an assessement of goals vs resources. Data demands are very large	It can depict precisely and quantitatively socio-economic drivers for unsustainable practices. It has been applied to analyses of ecologic feasibility of economic activities, to energy metabolism patterns and water scarcity topics in various countries and regions.	Yes, depends on the scale of the data.	Specific approaches are followed for each case. There are existing case studies for developing countries.	Yes	Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., & Ripa, M. (2019). Characterizing the metabolic pattern of urban systems using MuSIASEM: The case of Barcelona. Energy Policy, 124, 13-22. Giampietro, M., Mayumi, K., & Bukkens, S. G. (2001). Multiple-scale integrated assessment of societal metabolism: an analytical tool to study development and sustainability. Environment, Development and Sustainability, 3(4), 275-307. González-López, R., & Giampietro, M. (2017). Multi-scale integrated analysis of charcoal production in complex social-ecological systems. Frontiers in Environmental Science, 5, 54. Serrano Tovar, T. (2014). Spatial analysis in MuSIASEM. The use of geographic information systems and land use applied to the integrated analysis of rural systems' metabolism. Tejedor-Flores, N., Vicente-Galindo, P., & Galindo-Villardón, P. (2017). Sustainability multivariate analysis of the energy consumption of Ecuador using MuSIASEM and biplot approach. Sustainability, 9(6), 984.

Tool	Characteristics	Usefulness in present times	Considers geographic distribution? (GIS integration)	Potential to be used in developing regions	Is it current?	Selected bibliography & Case studies
	and specific.					
Stock Analysis	It is used to quantify the materials embedded in buildings and infrastructure, additioanl components stored in soil or water. Could be beneficial for the understanding of urban mining. It can be calculated with GIS tools.	4D analysis, urban mining	Yes	If performed with GIS tools it is a standard methodology applicable to all regions where data is available.	Yes	Lichtensteiger, T., & Baccini, P. (2008). Exploration of urban stocks. Journal of Environmental Engineering and Management, 18(1), 41. Oezdemir, O., Krause, K., & Hafner, A. (2017). Creating a resource cadaster—A case study of a district in the rhine-ruhr metropolitan area. Buildings, 7(2), 45.

Table 3. Assessment of selected UM frameworks and tools.
Source: own elaboration based on Benavides (2017)

Short list of UM frameworks

From the examples illustrated in Section *Step 2B: Assess the UM frameworks available* it can be appreciated that MuSIASEM and EUM are frameworks used to analyze the UM and obtain some sort of GIS representation. Furthermore, MFA is a preferred method for the flow quantification; nonetheless, there are specific customizations of the MFA method for each case, which are not known in detail for these examples. Merely the REPAiR project illustrates the details of its own MFA developed, the AS-MFA (Geldermans et al., 2017).

Furthermore, considering the UM approaches listed in **Table 3**, the tools that depict a possible GIS integration, applicability in developing regions and that are current are: EUROSTAT, UMAn, EUM, Baccini-Rechberger-Brunner method (MFA), MuSIASEM and Stock Analysis. From these, UMAn and EUM are frameworks that use basically EUROSTAT method/indicators and therefore their utilization on other regions requires adaptations of the data to EUROSTAT standards. Additionally, the Stock Analysis is an option that is limited mostly to infrastructure, in this case, flows and additional factors of the UM may be lost.

For practical reasons, it is considered that frameworks that already present examples of GIS representation are the best options to explore. Nevertheless, the UMAn framework is also considered a valuable option. As a result, three frameworks are short-listed:

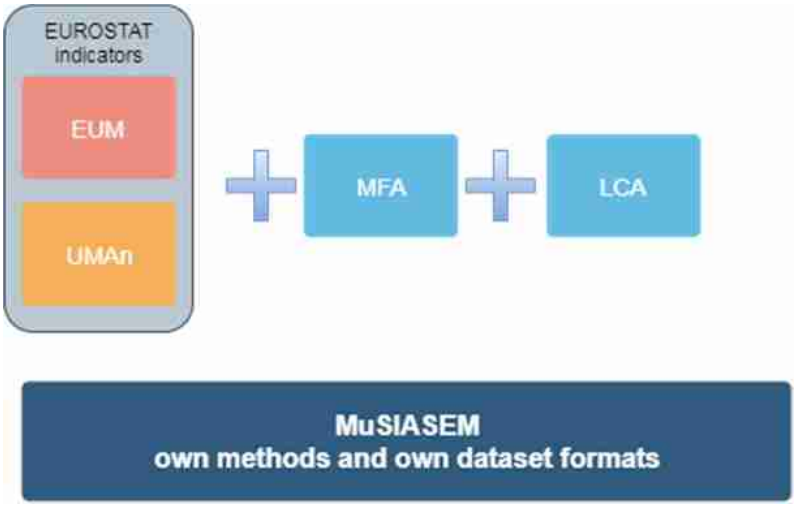

Figure 9. UM frameworks recommended for further analysis.
Source: own elaboration

Step 3: Relation between UM models and software tools

In Table 4 are depicted the different combinations of the GIS tools and UM frameworks selected in short lists from the assessments in the previous sections. Here are identified relevant characteristics of the UM frameworks that should be considered for the representation of results in GIS.

GIS Tool	UM Framework		
	EUM	UMAn	MuSIASEM
	MFA + LCA		
QGIS	Includes socio-economic and ecological variables that could be represented. This depends on georeferenced data availability.	Improves the understanding of origin/destination of flows. This might improve the georeferenced data availability. GIS representation depends on dataset scale.	Requires land use maps for calculations. The model might hardly provide real flow trajectory. GIS representation depends on the availability of georeferenced information
ArcGIS	Includes socio-economic and ecological variables that could be represented. This depends on georeferenced data availability.	Improves the understanding of origin/destination of flows. This might improve the georeferenced data availability. GIS representation depends on dataset scale.	Requires land use maps for calculations. The model might hardly provide real flow trajectory. GIS representation depends on the availability of georeferenced information

Table 4: Relation between UM frameworks and software tools
Source: own elaboration

It is important to notice that the same observations have been recorded for both GIS tools. This is due to the similarity in performance from both in terms of functionality, format flexibility and availability of support. The main difference lays in QGIS being open source and ArcGis being license based. The final selection of the tool, in addition to technical reasons, may obey to project specific factors like budget, pre-existence of software licenses or availability of a programming team for customization of results.

Furthermore, a common concern for the three UM frameworks might be the availability of the dataset for the UM analysis in different scales (national, regional, local; etc.). This limitation might be overcome by means of interpolation, which is as well, supported in both GIS tools. Nevertheless, the applicability and relevance of such method should be assessed for each particular case.

Finally, considering the analysis in Table 2, a definite selection might come as well in terms of the specific capabilities of the existing plugins for representation of flows in each GIS tool.

Step 4: Recommendation

Based on the analysis presented in Table 4, it can be seen that the three UM frameworks discussed have a large potential of further development for GIS representation. Nevertheless, from the examples presented it is observed that MFA as a method for UM quantification is more utilized. This method provides the flexibility of utilizing either the EUM or the UMAn frameworks, which might be an advantage for the analysis. Furthermore, the information about the method setup, its software-assisted calculation and discussion of results is well documented, which provides the flexibility to adapt the method, as in the case presented with the REPAiR project.

On the other hand, for MuSIASEM, the methods, dataset formats and procedures are specific to this framework and might require a deeper understanding. In fact, as stated by Serrano-Tovar (personal communication, April 9, 2019), for every case study, a customized version of the possible dataset with a high degree of manual work with Excel spreadsheets is required. This reflects the necessity to deeply understand the framework and how its own developed “grammar” works. Moreover, the plans for a standardized version of dataset are not being developed for the moment (Renner, personal communication, April 18, 2019).

Considering this, either EUM or UMAn as underlying frameworks is recommended. Furthermore, QGIS as a GIS tool is preferred due to the ready-to-use plugins found and its open source condition. Nevertheless, ArcGIS is considered as powerful and stable enough.

Annex A: Researchers and contacts in the different projects

MUSIASEM

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Metabolism of cities

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.FABRICations

https://www.fabrications.nl/#section-what-we-do

Annex B: Additional software and tools for urban simulation, urban planning and UM

UrbanSim, SUNtool, and UMI are important to understanding how targeted features within an urban environment perform. These urban simulation packages are designed for specific areas and with specific goals.

UrbanSim: http://www.urbansim.com/urbansim

SUNtool: "Robinson, D., Campbell, N., Gaiser, W., Kabel, K., Le-Mouel, A., Morel, N., ... & Stone, A. (2007). SUNtool–A new modelling paradigm for simulating and optimising urban sustainability. Solar Energy, 81(9), 1196-1211."

UMI: http://web.mit.edu/sustainabledesignlab/projects/umi/index.html

Other projects and tools that might provide further support for UM analysis are:

iTEAM: https://trimis.ec.europa.eu/project/iteam-integrated-transportation-and-energy-activity-based-model

CitySim: https://www.epfl.ch/labs/leso/transfer/software/citysim/

Metabolism of cities

The online project https://metabolismofcities.org has an important database with information about projects, thesis and papers on UM. Additionally, the site provides an online tool for MFA called Online Material Flow Analysis Tool (OMAT) and it is available at: https://metabolismofcities.org/resources/tools/omat

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