TOWARDS A MICROFOUNDATION OF URBAN METABOLISM

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Abstract

By recalling the theoretical approach derived from the conceptual framework of Societal Metabolism the paper is focused on the relevance of renewing the concept of urban metabolism in order to better address urban environmental impact toward a more efficient metabolism of cities. Among other issues, prevention and reduction of urban solid waste have to be primarily taken into account since waste represents an enormous loss of resources in the form of both materials and energy and at the same time may produce a considerable environmental impact. Waste production is an important quantitative and qualitative indicator of how much efficient an urban system is, particularly in relation to the use of natural resources.

The study proposes an improvement of conceptual framework and methods so far developed for studying and operationalizing the urban metabolism framework. By adopting the model of urban regulation regimes the way stakeholders influence the urban metabolism is investigated to catch the emergence of patterns at urban macro level. The objective is to provide an holistic model where urban metabolism emerge at the macro-aggregate level of the city as a result of the behaviours, practices and interactions of agents and actants at the different levels of the urban system (households, enterprises, corporate actors, communities and local public authorities).

Keywords
urban metabolism
practice theor
micro-macro links

1_The state of the art in Urban Metabolism studies

1.1_Conceptual framework

In order to explore how much energy and how many materials are consumed by human systems, scientist use *metabolism* as a metaphor of all the socio-economic and natural processes by analogizing the city to an organism: the city grows by absorbing nutrients from outside its boundaries and discharge the waste to its environment. But more than only a metaphor, *metabolism* is a theoretical category useful to understand, explain and accounting the relation of human systems to its environment so that *societal metabolism* is an input/output mechanism aimed to maintain the turnover connected to the conversion of matter and energy in useful things, an intrinsic feature in the reproduction of any organism (Padovan, 2014). By adopting metabolic approach socioeconomic researchers allowed to introduce the tools developed during more than a century of research on ecological systems and their metabolic processes to improve the processes of socioeconomic systems.

Whatever the system to which it is referred (city, household, firm), metabolism corresponds to the whole process of reproduction of the system itself and of its parts. Among metabolic approaches we can find Industrial Metabolism, Urban Metabolism, MuSIASEM approach (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism), Household Metabolism. Any of them have their specific quantitative methods of analysis of metabolic exchange between social and natural systems. Even if these different approaches are closely interwined, in the following we focus on Urban Metabolism, since urban systems are gaining more and more relevance in the organization of human activities. According to the UN-HABITAT's Cities and Climate Change global report on Human settlements 2011, the world's cities are responsible for 75 per cent of global energy consumption and up to 70 per cent of GHG emissions, while occupying just 2 per cent of its land and being home to just half of the global population (Padovan et al , 2014). As the demands for higher inputs of materials and energy to sustain the growth of cities continue to increase, understanding the metabolism of cities becomes extremely important for policy makers and decision makers.Cities present both the problems and solutions to sustainability challenges of an increasingly urbanized world (Grimm et al., 2008).

Urban Metabolism (UM in the following) is a multi-disciplinary and integrated platform that examines material and energy flows in cities as complex systems as they are shaped by various social, economic and environmental forces. Similar to biological organisms and ecosystems, cities cycle and transform incoming raw materials, food, water and fuel into physical structures, biomass and waste. Factors such as urban structure, form, climate, quality and age of building stock, urban vegetation and transportation technology can influence the rate of a city's metabolism (Holmes 2012) where the efficiency of metabolic process are measured as the ratio between inputs and outputs.

During the 50 years since the concept of urban metabolism was proposed (by Wolman in 1965), this field of research has evolved slowly. On the basis of an analogy with an organism's metabolism, the concept of urban metabolism has become an effective method to evaluate the flows of energy and materials within an urban system, thereby providing insights into the system's sustainability and the severity of urban problems such as excessive social, community, and household metabolism at scales ranging from global to local. Other scholars believed that it was not suitable to treat cities as if they were organisms.16 Instead, they believed that cities represent hybrid systems that combine multiple organisms, including humans, animals, and plants, in ways that are more similar to an ecosystem than to an individual organism. It then becomes possible to simulate material cycling and energy flows using knowledge and tools from ecosystem research (Zhang et al 2014).

With respect to this 'positivistic' framework, even if it is useful and reasonable, it is worth to recall two remarks. First of all, cities are not only physical entities but also symbolic, social, cultural machines. As a result UM may consist of not just material and energy cycles but also of highly politicized physical and social processes. These scholars move away from a society-nature dualism to seeing the city as a process of metabolically transformed nature, a dynamic intersection between social and bio-physical dimensions to urban space, even a socio-natural hybrid or a cyborg of machine and organism (Padovan 2014). Second, there is a crucial difference between a living organism and the social system. In the case of individual living organisms, the exchange of matter and energy with their environment is oriented to the simple non-teleological reproduction of the organism itself. In this case, modalities of recovery and transformation of the necessary elements for the reproduction of the organism's life change very slowly in time and above all, when they reach a balance, they are maintained over time. The social or socio-economic metabolism instead is not oriented to an equilibrium condition, but to continuous growth. For social sciences there aren't any limits to the physical growth of the objects to consume and reject in the environment, in a word in the growth of whole social system.

The latter remark recalls issues directly connected with sustainability of UM and in particular with consumption of resources and emission of wastes. Too fast and linear metabolic processes overcome social stability generating crisis, as for instance the rift between consumption and resources availability and flows that are predominantly linear or that form open loops (i.e., losses from the system) are not sustainable. Therefore, it is essential to encourage circular material flows and, as much as possible, transform wastes into resources. The former call for a renewing of the conceptual so as of the methodologies applied in studying UM processes. The two are linked in the sense that several research challenges, described in the next section must be resolved before it will be possible to encourage practical use of urban metabolism research to support decisions and policy development by urban planners and managers.

1.2_Methodologies

The methodology to undertake a UM study invokes the principles of conservation of mass and energy. Ideally this requires quantifying all mass and energy flows into and out of a city – including changes in storage – over a calendar year. In practice, however, the urban metabolism is quantified as urban inputs, outputs, and storage of energy, materials, nutrients, water, and wastes. At a first level of engagement, urban metabolism is usually studied or quantified by aggregate measures (though not precluding finer scale analysis) such as total annual electricity use or water consumption. This is analogous to human metabolism, which is measured by aggregate indicators like total energy or oxygen input per day. (Kennedy et al., 2014

This is the common methodological basis over which different methods and approaches have been developed by researchers, mainly in the last two decades (Zhang 2014).

The starting point is represented by the so called *black box models* in which the internal components of the system were not considered. Black box models reflect the overall inputs and outputs of a city and its activity intensity and scale to provide a macroscale indicator, analogous to human information such as weight, temperature, and blood pressure. Black box models can be used when little data is available and provide an overview of urban metabolic efficiency and the degree of sustainability.

In contrast, *subsystem models* try to open the black box to reveal its components. These models describe details of the flows among subsystems and the factors that influence these flows and are analogous to examining individual human organ systems (e.g., the heart and blood vessels); however, this requires much more detailed data.

Finally, *simulation models* have also improved as researchers accounted for circular metabolic flows for livability and for the network characteristics of systems. On the one hand, network models go beyond the traditional black box approach to analyze the internal characteristics of an urban metabolic system by transforming processes and nodes into mathematical descriptions of the flows among pairs of components. On the other, in addition to static models that focused on the value of a parameter (such as metabolic efficiency) at a given point in time, researchers have developed dynamic models that account for changes over time.

Looking at these experiences from the perspective of the research object, from the foundation of UM approach, two categories of research methodologies have been so far adopted. One refers to the *element-based* method (e.g., material flow analysis, life cycle analysis …) focusing on the specific element flows and stocks of urban ecosystems with a range of aggregated indicators. The other, *structure-based method*, e.g., ecological network analysis, is also introduced to explore the urban metabolism via the layout and functioning of urban ecosystems underpinning their industrial and biophysical processes, which uncovers the black box of urban ecosystem and pursues ‘strong sustainability’ by tracking mutual relationships control pathways among various socio-economic sectors and surrounding environment.

Thus, UM research seems to have evolved to the point at which it can now provide important insights into the functioning of an urban system studies by being evolving from models of linear to cyclic processes and then to network models. But notwithstanding this process of growing methodological complexity, the most common framework adopted in UM studies still remain Input-Output / Stock and Flows models based on the measurement of a number of macroindicators[1] (see an example in table 1) within a black box model (scheme A in figure 1) that considered only overall inputs and outputs or in a more advanced detailed model that examined (maybe through a network approach) the inner workings of the urban system (settlement dynamics) in increasing detail (Scheme B in figure 1).

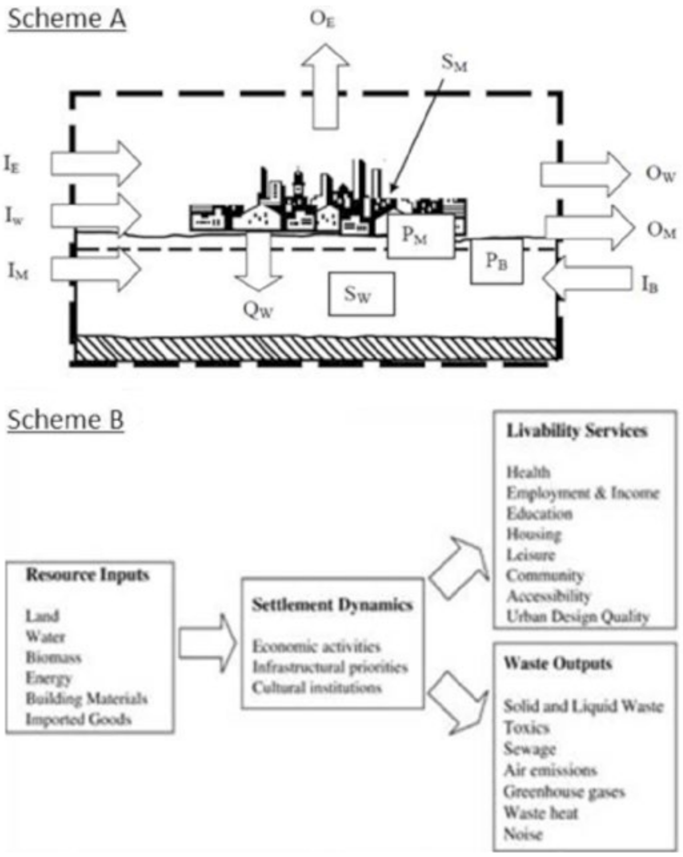

Figure 1. Two I-O schemes of Urban Metabolism: Scheme A (Kennedy 2014) showing inflows (I), outflows (O), internal flows (Q), storage (S) and production (P) of biomass (B), minerals (M), water (W),and energy (E) Scheme B (Newman, 1999) Extended metabolism model of human settlements

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[1] A list of the most common indicators organized by four different dimensions of the I-O model is provided by Hoornweg (Hoornweg D.et al 2012): INFLOWS (Food, Water-imports, Water-precipitation, Groundwater abstraction, Construction Materals, Fossil Fuels, Electricity, Total Incoming Solar Radiation, Nutrients); PRODUCED (Food, Construction materials); STOCKS (Nutrients, Construction materials, Landfill waste, Construction demolition waste); OUTFLOWS (Exported Landfill waste, Incinared waste, Exported recyclables, wastewater, Nutrients, SO2, NOx, CO, Volatile organics, Particulates, Methane, Ozone, Black Carbon).

2_One step beyond

2.1_Strengths and limits of the current approach and methodologies

The Um framework as briefly described above shows a number of useful features in order to face the comprehension and management of the increasing growth of cities and related demands for higher inputs of materials and energy and namely: identification of the system's boundaries; accounting for inputs and outputs to the system; call for an analysis of policy and technology outcomes regarding sustainability goals; integration of social science and biophysical science/technology.

Behind these advantages stands first of all the effort to provide a rigorous tool for analysing relevant energy and materials pathways at different scales that can lead to the development of management systems that increase resource use efficiencies, recycling of wastes and conservation of energy. Notwithstanding the different approaches to the analysis of metabolic processes, it is possible to identify some relevant concepts and tools that have been recognized as a common heritage of the UM approach (Holmes et al):

- **Emergy** is the available energy used directly or indirectly to make a product or deliver a service (that is the 'embedded' energy) It measures the work of nature and humans in generating products and services and serves as a common metric of environmental and economic values thus connecting ecosystems and socio-economic systems.
- **Material Flow Analysis**. Based on the principle of mass conversion (where mass in = mass out + stock changes), MFA measures the materials flowing into a system, the stocks and flows within it and the resulting outputs from the system to other systems thus providing a system level understanding of how a city, region or nation functions.
- **Life Cycle Assessment**, aimed at evaluating the potential environmental impacts of a product system throughout its life cycle by providing a cradle-to-grave assessment of a process including direct, indirect, and supply chain effects.

More in general, results from the application of an UM framework can aid planners and managers to improve resource use in cities; to reduce environmental degradation; to identify environmental impacts of energy, material, and waste flows; and to isolate problem areas in need of attention. It is noteworthy that the establishment of these common tools may represent at the same time the strength and the limit of the UM approach as it has developed so far. In fact most research on the flows of materials and energy has concentrated on traditional accounting methods and on establishing a technical framework. What is missing is first of all a real standardization of the UM paradigm since in the practice the tools above described may be based on heterogeneous data. In fact, even at the aggregate level, there are several measures of energy and material flows in the urban metabolism in large part because data collection is a formidable challenge and not every urban systems is covered by information in the same way.

A second critical aspect is the need for a correctly implemented multilevel approach that is find a way to explore and combine the results of analyses at different scales. Researchers usually treat cities as homogeneous structures and use data compiled at a relatively coarse resolution (e.g., using top-down methods) and ignore the differences within the city, such as differences between central and suburban areas. In addition, few researchers have combined studies of material and energy flows with the locations of the flows or with the activities and humans that produce them.This has resulted in a lack of research based on high-resolution data (e.g., bottom-up methods). If UM has so far not been widely used to support urban planning and management is mainly because the aggregation of data at urban or regional levels cannot show the details within an urban system that are the target of planners and managers.

The third crucial aspect is the most relevant in constraining the explanatory power of UM approach and pertains to the dramatic underestimation of the social component of urban metabolic processes. Urban metabolism is made by bundles of everyday life activities aimed at the stable and recursive reproduction of social material life of human beings. They are the basic units of metabolism, the triggering activities that start metabolism while at the same time they are outcomes of metabolism itself. In analysing UM has to be kept in mind that its processes of UM can vary consistently depending on different social configuration of the urban systems themselves (relation between technical progress and nature appropriation and between accumulation dynamic and social reproduction) and the specific ways by which UM is desinchronized with its environment are determined by a heterogeneous constellation of social practices (Padovan 2015). Urban systems cannot be considered as an homogeneous whole and the consideration of relations among different subsystems it is not enough to effectively open the black box of the metabolic processes. The activities carried out by the agents at the micro-individual level have to be taken into account to reach a sound understanding of the mechanisms that determine the overall effect in terms of material and energy use by the urban system.

From the above remarks clearly emerges the need for a multidisciplinary approach that holistically accounts for all of the social, economic, and ecological drivers that are responsible for the flows among the components of an urban system and the changes in these flows over time.

2.2_A new approach for UM analysis: practices, complexity and emergence of macro-behaviours

UM is the outcome of complex arrays of social practices and activities that change over time and it is a matter of regulation, which requires a decisional perspective. Urban metabolism must be approached as a dependent variable to be explained. Part of this explanation depends on environmental factors independent of human intervention (at least at the urban scale considered). The remaining part depends on an emergent systemic configuration of practices affected by many factors.

Recalling what above introduced, a city is not only a metabolic unit but also a social system. Making sense of the triggers of the metabolism of a city and the way one may apply such triggers, so that metabolism may shift towards greater eco-efficiency, requires a understanding of the political, institutional and cultural factors that affect how a city’s use of matter and energy (i.e., its economy) works. To renew the UM conceptual framework two perspectives of analysis must be considered:

- **Regimes of urban regulation.** A mode of regulation is an emergent ensemble of social practices, rules, conventions, patterns of conduct, organisational and institutional forms that can stabilise a metabolic regime. The regulation approach focuses on the ‘regularities’ (and their disruption and change) one can observe in the functioning of a urban system. A list of regulatory devices should include also what may be called material arrangements and ‘sociotechnical regimes’, that is, technological artefacts and devices working in connection with households practices or composed in expert systems.
- **Agents and practices.** Patterns of resource consumption mostly depend on daily practices performed by different agents. More than population density or settlement patterns, modes of institutional, organizational and social practices directly affect resources use. Cities generate bundles of social practices that affect resources access and use, often increasing severe social inequalities. Growing groups of people – mainly aged, migrants and alone women – are undergoing difficulties in energy, food and housing access and provision. Phenomena such as food deserts, obesity, scarce mobility, are spreading up with an unusual speed. Recovering, energy and mobility access is also moulded by social position, ageing, income, residence. For all these aspects we can speak of “positional consumption” of resources. The positional consumption not only affects the ways and extents of consumption but also the generation of waste.

More in details, it is worth to underline three aspects related to the study of urban agents’ practices:

1. the most relevant factors underlying urban metabolism mechanisms are the practices of household members. Among individual agents at micro level, we consider households neither as isolated units nor as small units of social organization but instead as basic units of an emerging system. Household consumption is ultimately the core of social system reproduction and the research efforts must be oriented in investigating how changes in behavioral patterns at the household level influence other actors.
2. households practices as units of analysis can be regarded as including a variable mixture of reflective choice, unreflective behaviour based both on actual or perceived constraints and on habit or the particular way a space of choice is presented. Choices, incentives and constraints depend on four elements: rules (formal or informal); ideas; socio-technical affordances; and finally money, as a symbolic mediator of relationships capable of affecting the affordability ranking of performances in most (if not all) problem-situations.
3. these elements, in their turn, mediate the relationship among households and the other types of agents, according to their own rationales:
   - for local government actors, we can distinguish three basic styles of action: authority, provision and enabling.

- for corporate actors we can distinguish between: steady (business-as-usual), reactive (behavioural changes according to perceived) and pro-active (changes are anticipated and even promoted).
- for civil society actors we can distinguish between initiatives of a public or private character.

2.3_A new model for UM assessment: objectives and tools

A different conceptual framework calls for different methodological tools. The Input/output models, even in the evolutionary and dynamic version represented by the adoption of a Stock and Flows paradigm (based on System Dynamics techniques) keep the analysis at a high aggregation level (cities or subsystem). This level of observation, even if might provide an accurate description of UM patterns, doesn't allow the needed 'bottom-up' approach that is the identification of the mechanisms that drive the emergence of these patterns starting from the individual practices.

The goal of a renewed UM analysis is in fact to reconstruct the factors impinging on the systems of practices in which actors' behaviour finds its place and the connections between the different types of agents (households and civil society groups, corporate and local government actors) in order to provide effective knowledge to design future climate policies. This means detailing actors, regulatory and institutional configurations, tools of regulation (incentives, rules, socio-technical affordances, information campaigns and other sources of ideas, innovation strategies at the corporate and civil society level) and their significance, identifying the drivers, dynamics, possible conflicts and tensions through which sustainability-related processes are organized, transformed and relationally interconnected.

To reach this objective we currently need to build complex scenarios that explicitly explore the impact of different urban evolutionary trajectories, that can drive the designing of different reasonable policy alternatives. Such scenarios would allow evaluating the social and economic "costs" and "benefits" of long-term climate goals. It is noteworthy that there can be very different ways/policies to achieve low-carbon cities, and these ways cannot be decided by experts and politicians alone but might consider the participation of a wider public of urban actors in providing knowledge so as in evaluating decisions.

Three methodological approach seem to be appropriate to reach these objectives:

Scenarios building via backcasting approach. The backcasting represents a step beyond the conventional scenarios approaches that are mainly based on a 'push model' based on "drivers behind" factors. Backcasting approach is a 'pull model' based on factors of attraction. It is framed as the actual analysis of how to attain desirable futures, i.e. the process of working backwards from a particular future end-point to the present to determine what measures would be required to reach that future. It starts by identifying desirable futures and then looks backwards from that future to the present in order to design roadmaps to achieve it. Backcasting has gradually become more widely applied over the last decade for its strongly normative concept of sustainability. Backcasting works through envisioning and analysing sustainable futures and subsequently by developing agendas, strategies and pathways to get there. This has attracted attention from policy-makers in many countries, as well as scientists outside foresight and sustainability studies.

Agent Based Simulation. Agent Based Modelling is a computational method which adoption in Social Sciences has been fast growing in recent years mainly for its capability in grasp the complex dynamics of social phenomena. Building an ABM means recreating by computer simulation the phenomenon we're focused on by using information and data (provided by official statistics and public engagement) in order to modelling individual behavior (model calibration) and, by running the model, obtain a macro results to be compared with the observed reality (model validation). At the end of this process explanatory model is provided (a possible explanation, not statistical probable) that can be used to forecast, represent different scenarios, verify theoretical assumptions or just describe the observed reality.

Finally, it should be a noticeable improvement (even if not easy neither low-cost to implement) adopting tools for an effective **Public engagement**. This approach may result in a wide range of practices going from the construction of a shared framing of the problems, through the sharing of diffused knowledge to a realized deliberative democracy (e.g. participatory budgeting). The complexity of UM assessment, in fact, calls for this public engagement since it entails an interdisciplinary approach whereas physical, economic and social indicators have to be merged and harmonized in order to draw a picture of UM. The plausibility of this picture is closely connected with the participation of the urban actors above defined (households, corporate actors, public administration and communities) since a shared vision of the UM among the actors is needed in order to mobilize knowledge to better define problems and find effective solutions. A lot of tools have been developed to support this approach but among these tools for public engagement are gaining a central role some practices (more or less formalized) referred to the concept of *crowdsourcing*. Crowdsourcing provides support for managerial decision making, problem solving, and opportunity exploiting. The crowd (contributors or solvers) generates ideas and may also be involved in analysing and prioritizing proposed solutions to problems. To understand the natural, social, and economic frameworks in which resources are consumed it is necessary to involve both policymakers and local stakeholders in urban metabolism research to ensure that planners understand the implications for those who will be affected by their plans.

The general idea to be implemented, thus, is a three-steps methodological process: a) identifying scenarios by adopting a backcasting approach (combined with roadmap designing) for the conceptualization of different trajectories ; b) validation of the scenarios by the engagement of experts, decision makers and wider public; c) operationalisation of the scenarios validated by using Agent Based Modelling techniques. Figure 2 shows, as an example, a simplified scheme of a UM model drawn on the basis of the proposed UM conceptual framework and aimed at defining trajectories to reduce metabolic processes with particular attention on the production of waste.

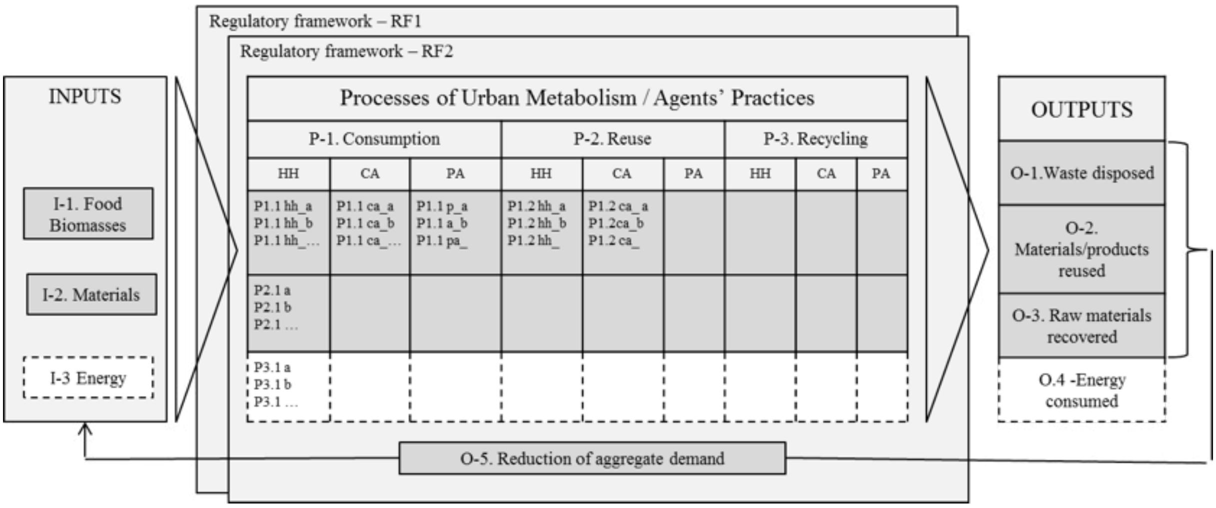

Figure 2. A Conceptual scheme of a UM Agent Based Model.

The model is characterized by few distinctive elements:

- **a.** Individual agents are HouseHolds (HH), Corporate Actors (CA), Public Administration (PA).
- **b.** Individual agents are situated in different Regulatory Framework (RF1, RF2) referred to different institutional and normative context.
- **c.** Individual agents act following different strategies/practices: Consume (P1), Recycle (P2), Reuse (P3). They act all along the waste chains referred to different inputs in the urban system (I1,I2,I3).
- **d.** The cross consideration of strategies and inputs will allow to define different specific practices for each type of agent (labelled in the figure with the alphanumeric code 'p_Input.Strategy_Agent_n of practice') and for each Regulatory Framework.
- **e.** The most important. Even if extremely simplified, the figure clarifies the crucial conceptual element of the framework: the Input-Output flows is decomposed/recomposed from the macro to the micro level and the overall effect in terms of metabolic processes is determined by practices at individual level.

To feed such a model a huge amount of different data are needed and namely: quantitative data form statistical institutional sources, knowledge about current and possible normative and policy frameworks, qualitative information about individual behaviors derived from the engagement of experts and wider 'crowd'.

Once data and information are collected, the design of reasonable scenarios can be carried out by working on the interplaying of the different elements at the di different level of the model: individual practices, norms, amount of inputs and so on. Finally, the implementation in an Agent Based Model will provide not just the description and representations of different scenarios but, more important, some measures of the connected outputs. That is an assessment of the sustainability of alternative policies.

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