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MULTI-FUNCTIONAL LAND-USE PLANNING AS A REGULATOR OF URBAN METABOLISM: A CONCEPTUAL PERSPECTIVE

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This paper is an attempt to reveal the possibilities for using land-use planning to improve the urban metabolism (UM) circularity and sustainability, and thus its usefulness for urban planning and development. The available literature about UM is overviewed and analysed from this conceptual perspective, and a comprehensive and consistent definition of the UM concept is proposed. The Circular UM is also presented as an efficient and sustainable extension of UM. It has been found that distinct urban forms strongly influence UM, and that this influence to a great extent transfers through, and connects, the layers of the urban form, from the urban morphology, through the spatial distribution of urban functions, to the level of the building stock. These relations imply that proper intertwining of city functions in compact urban areas could have favourable impacts on many aspects of UM, reducing the consumption of land, material and energy, as well as pollution, and improving the overall quality of life. Quantification of these impacts requires a more precise determination of the effects of intertwining of urban functions, and the side-effects of doing so, and is a precondition for the effective use of MLU for UM optimisation.

***Key words*: urban metabolism, circularity, sustainability, multi-functional land use, intertwining of urban functions.**

INTRODUCTION

Despite numerous activities undertaken with regard to environmental protection, our planet is at a critical crossroads, and the choices that humanity makes will have a significant and lasting effect on all life on earth. For a long time, environmental protection and sustainability were focused on areas outside cities and the protection of natural rarities, isolated landscapes, and wilderness (Vasiljević, 2012). However, due to high concentrations of people, goods and activities, it has turned out that cities have a crucial impact on global sustainability (Kennedy *et al.*, 2007; UN General Assembly, 2016; Pistoni and Bonin, 2017), forming some kind of critical points, which are particularly vulnerable to natural and man-induced catastrophes (Antrop, 2006). The United Nations Department of Economic and Social Affairs (2014) reported that in 2014 there were about 7.3 billion people on the planet, with 54% of them (about 3.9 billion) in cities. The estimate for the total population in 2050 is 9.8 billion, of which 66% i.e. 6.5 billion will live in cities, which is almost double the 2014 figure and close to the total human population on the planet in 2014.

According to Global Footprint Network estimations, current consumption of resources exceeds the planet's capacity by 56%, and with this trend the consumption in 2050 will be double what is sustainable (Ávila, 2018). Cities are large consumers of various resources and they generate huge amounts of waste, thus making a vast impact on the environment. Urban areas are responsible for 60-80% of global energy consumption, 75% of global carbon dioxide emissions and 75% of global resource consumption (Swilling *et al.*, 2013). The result is the loss of agricultural land, forests and other natural habitats, the reduction of biodiversity, and air, water and soil pollution. In that way, the environmental footprint of cities deepens over time and worsens not only the quality of life in them, but also global environmental conditions (Kennedy *et al.*, 2010). Therefore, big cities appear to be the greatest obstacle to sustainable development, especially in less developed countries with an intense urbanisation process (United Nations Environment Programme, 2017). Consequently, it is difficult to achieve a balance between often conflicting demands and expectations imposed by the quality of life in cities and environmental

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protection (Conke and Ferreira, 2015).

The aforementioned indicates that current urban development trends are alarming and indicate the need for change through adequate planning. Spatial and urban planners have developed numerous concepts and models to explain the functioning of cities and to solve complex problems that accompany life in them. One of them, the concept of urban metabolism (UM), which considers cities as "living organisms" (Wolman, 1965; Pinho *et al*., 2011), will be presented in this paper in more detail. The urban functions of housing, business, recreation, etc. are recognised as drivers of UM, determining energy and matter flows within a city, and between the city and its surroundings, and so a better understanding of these functions and of their relations can enable more efficient planning and development of cities. As a natural extension of the concept of sustainable development, the UM concept is particularly suitable for improving the urban development in that sense, too (Kennedy *et al*., 2010).

The rapid increase of urban population has led to a chronic lack of space in cities, and the role of space has become increasingly important, "both as an instrument and as a goal" (Lefebvre, 1992: 411), raising the issue of spatial planning and management. Land-use necessarily affects the urban metabolism in many aspects and at various levels, so insight into its influence is of great importance for the optimisation of city functioning. Therefore, it is surprising that very few among the increasing number of papers dealing with UM are devoted to its relationship with land-use planning, which has left many significant questions unanswered. In this paper, ways in which multi-functional land use (MLU) affects UM and the quality of life in cities are addressed, and possibilities for improving some important issues of city functioning are proposed.

The objectives of this paper are twofold. The first objective is to provide an insight into the UM concept through an overview and analysis of available literature, and on that basis formulate a comprehensive and consistent definition, and determine directions and areas for its optimal use. The second objective is to investigate the possibilities for land-use planning, especially MLU, for the optimisation of UM. This is done through the analysis of impacts that different urban forms have on UM; the conclusion drawn is that proper optimisation of intertwining city functions in compact urban areas can improve many aspects of UM.

THE CONCEPT AND DEFINITION OF URBAN METABOLISM

Motivated by rapid and intense urban development in the United States during the mid-20th century, Abel Wolman published a paper (Wolman, 1965) which is considered to be the beginning of the modern concept of UM, the roots of which can be dated back to the mid-19th century and the work of Karl Marx (Zhang, 2019). In his paper, Wolman tried to identify reasons and to offer solutions for the deterioration of the air quality and water supplies in American cities. For that purpose, he analysed the "metabolism" of a hypothetical American city region with one million inhabitants, which included the inputs and outputs of energy, water, materials and waste, establishing the framework and basic features of UM (Wolman, 1965). Patrick Geddes also contemplates cities as living organisms which consume resources from, and excrete waste into, their surroundings (Pistoni and Bonin, 2017), or according to Decker *et al*. (2000: 715): "cities transform raw materials, fuel, and water into the built environment, human biomass and waste".

Now, after more than 50 years, the UM concept is neither completely elaborated, nor adequately defined (Latin *definitus* – determined, distinct). This makes it difficult to clearly and precisely designate meaning, features and scope to the concept, which must be overcome in order to improve the concept from descriptive to being applicable. To do that, it is advisable to start from the meaning of the words in the name of the concept. The word *urban* originates from the Latin *urbs*, which is used for a city, or something that has the characteristics of a city. The word metabolism originates from the Greek *μεταβολήσμός*, which means change. In biology, metabolism is defined as a set of interdependent processes, including nutrition, growth and reproduction, and the maintenance of structures and responses to stimuli coming from the surroundings, all of which make the life of cells and the organism possible (Voet and Voet, 2004). Although it came out of this "natural" definition, in many details UM cannot be equivalent to the metabolism of a living being. In an attempt to expand and improve Wolman's analysis that focuses on energy and matter flows, Kennedy *et al*. (2007: 44) define UM as: "the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste". Most authors (Wolman, 1965; Minx *et al*., 2011; Kennedy *et al*., 2014; Conke and Ferreira, 2015) agree that UM includes numerous processes which use and affect the flows and transformation of energy and matter in the city, human activity, and the interaction of the city with its surroundings. All of the previously mentioned can be embraced by the definition that: "UM is a complex process that involves numerous, diverse and mutually conditioned relations and interactions which determine the flows, transformation, and exchange of energy, matter and people within the city, and between the city and its environment". In order to make this (or any other) general definition of UM practically applicable, one must have in mind that every healthy metabolism *per se* entails the functioning by which all elements of the "organism" work to optimally support it, leading to the fulfilment of the purpose of its existence, in the sense of Aristotle's τέλος (purpose, reason i.e. cause of existence). This significantly limits the large number of possible solutions that the complex concept of UM offers, and directs them towards the desired goal: an organised and functional city which exists for the benefit of its inhabitants.

The components of Urban Metabolism

Although a holistic approach in spatial and urban planning is not new, and can be traced back as far as the end of the 19th century and Ebenezer Howard's Garden City (Xu and Madden, 1989), it is still poorly integrated into the UM concept. As a matter of fact, one of the major shortcomings of current UM applications is that they neglect the *raison d'être* of urban settlements: their social component. Better and safer living, achieved through the processes and functions of city, was the essential reason for forming the first urban settlements, or in the words of Aristotle: “men come together in the city to live; they remain there in order to live the good life” (Mumford, 1961: 111).

The social component of UM is manifested through the quality of the urban environment, its services, comfort, safety and similar parameters (Southworth, 2003), some of which are easy, and some more difficult to quantify. The difficulty of quantifying social components is probably the main reason why it is only occasionally analysed in UM studies; it is much easier to quantify and study the flows of energy and matter, and their economic and environmental consequences. A purely quantitative approach to UM has also been criticised by urban ecologists and urban sociologists, insisting that they should also be engaged in an integrated approach to planning urban areas (Lin *et al*., 2012). Such a comprehensive approach should enable the balanced and harmonised development of urban systems, i.e. development that is not selectively adjusted to specific interests, because this increases differences between the city residents (Davis *et al*., 2016). In particular, the selective control of urban space and infrastructure is known to lead to the uneven distribution of urban functions and related facilities, as well as the uneven density and quality of communal utility and traffic networks, making social inequalities more prominent (Janin Rivolin, 2017). This significantly affects the quality of life in cities and can lead to the formation of slums and the “death” of certain zones – sometimes even of entire urban settlements (Jacobs, 1961), indicating that sustainable urban development is impossible if some citizens are prevented from meeting their basic needs. If the goal is a sustainable UM, its economic, social and environmental components must be equally taken into account.

Circular Urban Metabolism

Cities are very complex “organisms”, and at the same time they are habitats for a multitude of beings – humans, animals and plants, which makes them specific ecosystems (Kennedy *et al*., 2010; Castan Broto *et al*., 2012). Natural ecosystems are sustainable if they have sustainable inputs of energy and matter, while food chain, decomposition and similar processes ensure that there is no real waste in their metabolism, as each output is the input for another process or organism. Thus, a significant amount of energy and matter is recycled within the circular metabolism of a natural ecosystem (Kennedy *et al*., 2010). If cities could obey similar principles, their sustainability and that of the area (region) they directly affect would be much better (Van Broekhoven and Vernay, 2018), which is especially important for cities that are large and significant on the global scale. However, cities are artificial (anthropogenic) systems with a predominately linear metabolism, and they require large flows of energy and matter. Resources enter a city as inputs into specific processes, and the waste produced leaves the city or accumulates in designated parts of the city, or its surroundings (Kennedy *et al*., 2010).

The purpose of the Circular Urban Metabolism (CUM) concept is to propose mechanisms compatible with those of the circular economy and industrial ecology, which would, as much as possible, transform linear flows of energy and matter that occur in a city into circular ones, thus reducing their negative impact on the environment and contributing to more efficient and sustainable use of the available material and human resources (Saavedra *et al*., 2018). By connecting different processes into loops, the waste from one becomes input for other processes, making the entire system more sustainable (Van Broekhoven and Vernay, 2018). It has already been anticipated that what we now treat as “waste” tomorrow could be a more suitable and cheaper resource than if it were obtained by primary exploitation, especially in terms of the concentration and purity of the desired material (Brunner, 2007). Although they share a common intention to connect different processes in the connected loops, CUM differs from the circular economy and industrial ecology by its tendency to treat economic, social and environmental issues on an equal footing. The city of Lille, France provides a good example of CUM: using anaerobic digestion, organic waste is processed into biogas and compost, thereby connecting waste management, energy, transport and agriculture and improving the environmental conditions (Van Broekhoven and Vernay, 2018).

However, one city is too small, and in many respects an incomplete system to ensure that the outputs from all processes taking place in it can be used as inputs for other processes, thus enabling a metabolism that would be completely circular and self-sufficient. It is easier and more efficient to establish circularity within a larger network inside a region, country, continent, or even globally, synchronising the city’s metabolism with its environment and with other cities from the network. In that way, the products of one city’s metabolism could be more efficiently used in neighbouring cities or settlements, rather than insisting on their use in their city of origin. Therefore, CUM needs to be extended to areas wider than a city that are sufficient to manage optimal networking and circularity. Such an optimised network is capable of providing extremely efficient circulation of energy and matter in the area in question. This has been in practice for decades between municipalities and cities in the area around Helsingborg and Malmö, in Skåne County, Southwest Sweden, making them a perfect illustration. The “symbiosis” of public and private companies inside a unique system of waste collection, sorting and treatment has made it possible to extensively (more than 80%) and efficiently process, recycle and reuse various types of waste, including the production of biogas and its usage in public transport and heating. Better quality biogas is used as a fuel for transport vehicles, and lower quality biogas is used for heating, especially in greenhouses, thus promoting sustainable gardening that would otherwise be difficult in that particular climate (Nordvästra Skånes Renhållnings AB, 2020).

LAND-USE PLANNING AND URBAN METABOLISM

The activities that occur in a city and its surroundings are initiated by the needs of its inhabitants, from existential needs, such as food, water and shelter, to more complex needs of an economic, political, social, or cultural nature. They are the drivers of UM, determining the flows of energy and matter, and the way of life in a city; there is no UM without them. These activities and processes, and the matter, energy and people flows they produce are connected into feedback loops, so it is necessary to study and understand their relationships in more detail (Dijst *et al*., 2018). The spatial organisation of these functions significantly influences their performance (*ibid.*), and so the optimisation of land-use is crucial to attaining an efficient and highly sustainable UM, thus improving the quality of life and protecting the environment affected by urban areas. The systematic classification and assessment of land-use options are necessary for deciding between various, often competitive, demands, and coordinating them with the existing natural conditions, application possibilities, and human needs. In that way, land-use planning procedures could ensure the efficient and sustainable use of land, and thus preserve the land resources for the future (Food and Agriculture Organization UN, 1993).

Multi-functional Land Use

Multi-functional Land Use (MLU) is as old as cities themselves, and implies "the implementation of more functions in a determined place in a determined period of time" (Priemus *et al*., 2000: 270). In order to have sustainable land-use, it is essential that MLU is conducted in a way that enables synergy of the effects of city functions, i.e. that the joint effect of their actions exceeds the sum of the effects of individual functions, thereby giving a new quality (Rodenburg *et al*., 2003; Van Broekhoven and Vernay, 2018). The selection of functions that intertwine in a particular city zone has a major influence on the quality of the MLU performance results. That choice should be natural and guided by experience; only the functions that are known to be compatible (the effects they produce support one another) or complementary (the effects they produce complement each other) should be intertwined. There are various methods for evaluating the complementarity and compatibility of city functions, but it should be kept in mind that besides the characteristics and features of locations, land-use should also consider the interests and desires of the local community. Low compatibility of intertwining functions can lead to significant side effects (externalities), which typically affect the economic, social and health aspects of life, and effective land-use planning should minimize them (Taleai *et al*., 2007). This could be achieved by land-use classification and development control (Willis *et al*., 1998), and analysis of the complementarity and compatibility of intertwining basic city functions, which was done by Taleai *et al*., 2007) using a combination of several techniques. As a measure of compatibility, the authors took the degree to which two or more functions can interweave in the same space and time with insignificant negative effects. They confirmed that an increase in the number of functions combined in one city area increases the overall negative effects, pointing out that in such cases, very careful planning is necessary. Rodenburg and Nijkamp (2004) made an attempt to quantify the MLU concept by introducing the degree of multifunctionality, which increases with an increase in the space heterogeneity and the number and degree of intertwining city functions.

Regulation of urban metabolism using MLU

Motivated by health and economic concerns during the final stage of industrialisation, and later formalised by spatial planning based on functionalism and zoning (Van Broekhoven and Vernay, 2018), the major city functions (housing, business, recreation, etc.) are usually spatially and temporally separated, limiting the ability to properly organise a city, and significantly degrading the quality of life of most of its residents. To remove the consequences of this approach, which are to various extents still present in many cities of the world, a consistent and up-to-date approach based on CUM and MLU concepts, which are complementary and well-adjusted to each other, can be used (*ibid*.). Since CUM implies a connected network of various processes and activities, MLU should be implemented in a way that supports this connectivity and circularity, and overcomes the separation of urban functions and formation of mono-functional city zones. Although a completely circular metabolism is not feasible within a single city, MLU can facilitate and support the local connection of some processes into loops, including the re-use of some types of waste, thus promoting circularity (*ibid*.). Jane Jacobs (1961), an ardent advocate of a multi-functional approach, has pointed out that multi-functional urban areas are more economically viable, safer and more culturally and aesthetically interesting than mono-functional ones. Also, Van Schaick and Van Der Spek (2008) suggest that intertwining different urban functions within the same city area results in conditions that, in multiple ways and at different levels, make living more comfortable. Over the past few decades, the idea of multi-functional city zones has become increasingly auspicious and gained numerous followers (Van Broekhoven and Vernay, 2018).

Research conducted by Pinho *et al*. (2011) shows that intertwining different functions in a particular space is more efficient if the density of the population and buildings, i.e. the space compactness, is higher, and that this intertwining reduces the need for additional building, thus reducing the pressure on free space in a city (parks and other green areas) and its surroundings (agricultural and forest land). Table 1 was constructed from the results presented by Pinho *et al*. (2011) to analyse the impact on UM of four basic types of urban form, each containing three layers: 1) *larger urban configuration*, which deals with the morphology of urban areas and population density; 2) *urban diversity patterns*, which deals with the spatial distribution of functions in an urban area; and 3) *urban building stock*, which deals with primarily residential buildings in an urban area.

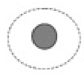
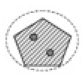
Table 1 aims to classify various types of each of the three layers into their appropriate urban form, and to establish how, and to what extent, the principal impact of the urban form on UM is transferred from layer to layer. Although cities are complex systems in which the transfer of any feature between layers cannot be complete and exact, the data presented in Table 1 clearly indicate strong correlations and a pronounced transfer of the influence of each urban form on UM through all three layers. It becomes evident that urban areas with a compact structure and higher residential densities have lower consumption of the main UM factors, energy and matter than those with a fragmented structure and low densities. An increase in compactness leads to lower consumption of material and energy per unit of built-up space and in the construction of supporting infrastructure, as well as to lower energy consumption for heating and cooling (Pinho *et al*., 2011). Since the construction and maintenance costs in such zones and their infrastructure are lower, the basic infrastructure is accessible to a larger population. More compact city zones also make the intertwining of urban functions and services easier, and thus significantly reduce the distances that people have to travel to meet their needs. This intensifies the use of non-motorized modes of transport and urban public transport systems, which together with the extensive use of communal heating systems, drastically reduces pollution from fossil fuel combustion (Ghafouri, 2016; Hsu, 2019).

school, in the street, etc.), leading to better cooperation and stronger support between inhabitants, a reduction in the crime rate, and safer, more pleasant and homely urban areas (Vreeker, 2004; Hsu, 2019).

It follows from the above mentioned that adequately optimised MLU is able to have a positive effect on important UM components, such as:

- Land consumption;
- Consumption of materials and energy for construction, and associated infrastructure;
- Energy consumption for heating/cooling;
- Energy consumption in transport; and
- Environmental pollution;

Tanle 1. Cross consistency assessment of human need in relation to lighting technologies (Source: Pinho et al., 2011)

layer	Type of urban form		Supposed impact		
			land consumption	energy consumption	material consumption
I	*high density, compact structure*		low	low	low
II	*monocentric model*		-	low	-
III	*high-density housing*		low	low	low
I	*high density, fragmented structure*		medium	medium	medium
II	*composite model*		-	medium	-
III	*high-density and medium-density housing*		low	low to medium	low
I	*low density, compact structure*		high	medium	high
II	*polycentric model*		-	high to medium	-
III	*medium-density housing*		high to medium	medium	high to medium
I	*low density, fragmented structure*		high	high	high
II	*urban village model*		-	high	-
III	*low-density housing*		high	high	high

Besides the positive economic and environmental effects that MLU can provide, it can also improve the social indicators of the quality of life in a city, such as the share of households connected to the electricity and water supply, sewage, and waste collection systems, (Conke and Ferreira, 2015). In addition, the harmonization of city functions (residential, work, recreation and leisure, culture etc.) enriches social interactions and promotes cohesion and association within the community. In compact and multi-functional city zones, social interactions are more frequent and diverse (in neighbourhood, in transport, at work, at

and in that way, it improves related aspects of the quality of life in a city.

However, together with the mentioned positive effects of MLU, an increase in density and compactness can lead to significant negative effects (externalities), especially if different city functions intertwined in space and time do not match well. The application of MLU in the past has often suffered negative effects because the economic aspect prevailed over social and environmental ones. A development that insists on higher densities and compactness, without considering other aspects of urban life, often leads to congestions problems, especially in transport, services and supply, including the electricity and water supply, and may increase the already existing deficiency in open spaces and green areas (Neuman, 2005). A higher concentration of activities and congestion problems can increase pollution in dense cities (Van der Waals, 2000), and the constant presence of large numbers of people in a small urban area can lead to overcrowding and loss of privacy (Vreeker, 2004). Therefore, an increase in compactness is desirable only in suitable city areas, under conditions that ensure that such an increase will not reach a level which produces significant negative side effects and a deterioration of the quality of life in the city.

CONCLUSION

In this paper, a comprehensive and consistent definition of the complex concept of urban metabolism (UM) has been proposed, with its utilisation directed by the notion that UM is "healthy", i.e. that it contributes to the efficient and sustainable functioning of a city, only, and only if all elements of the city contribute to its successful functioning as a whole, which implies much more than energy and matter flows into and through the city. It also implies that UM and other urban planning concepts should be based on an integral and circular (holistic) approach, rather than being sectoral and linear, including not only economic and environmental, but also social aspect of urban development. Such an approach requires the extension of urban planning to areas wider than cities in order to achieve optimal networking and circularity, and in return it could bring a balance between public and private interest.

Land-use planning has been recognised as a powerful tool for regulating UM, and some interdependencies and relationships between the concepts of UM and multi-functional land use (MLU) have been presented and analysed. It was observed that urban forms significantly affect the UM, and that this influence is to a large extent transmitted through the layers of urban form, from the level of the city morphology, across the spatial distribution of urban functions, to the level of the building stock. In that way, it has been shown that adequate spatial organisation of city functions and their proper intertwining can help to optimise UM and make it more sustainable.

Some important issues are still waiting for adequate development, such as more precise determination and quantification of intertwining urban functions, and a reliable methodology for estimating the upper limit of urban area compactness, below which the negative effects are acceptable (problem of externalities). These are topics for further study.

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