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ASSESSMENT AND MANAGEMENT OF URBAN ENVIRONMENTAL QUALITY IN THE CONTEXT OF INSPIRE REQUIREMENTS

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Abstract

The United Nations adopted the 2030 Agenda for Sustainable Development in 2015. Among 17 defined goals, in particular, the goal 11 deals with urban sustainability, resilient, population and air pollution. An effective decision-making is impossible without high quality truthful and credible data, data integrity, which describe the interactions between society and the environment in the increasingly urbanized world. Nowadays, data collection of urban environment monitoring and modeling systems generates so-called the Big Data which consists of such georeferenced parameters as weather conditions, pollutant concentrations and transport, in particular. From the other hand, the diversity and the interoperability of multi-source spatio-temporal data formats and structures in geographical information systems can siginicantly slow down the decision-making process of urban planning. Despite time-consuming data mining, we looked into an alternative knowledge-based intelligent method for urban metabolism analysis. Our approach is based on the infrastructures for spatial information which have been defined by the INSPIRE Directive of the European Union in 2010. Using the INSPIRE generic conceptual model, we focused on the user case in one of the major industrial cities in Ukraine, namely, Krivyi Rih, where urban methabolism is very dependant on fosil emmission and pollution rather than on renewable and green energy resources. The innovative indicators of material-energy flows were developed by the authors. Using those indicators, ArcGIS-based classification, cathegorization and modelling of urban metabolism of transportation subsystem were carried out. The simulation results showed that the efficiency of urban metabolic directly depends on a number of electromobilies on streets and the annual car mileage. In our study we demonstrated that the new indicators of material-energy flows are applicable. In the Krivyi Rih case the estimated efficiency of urban methabolism of 40% can be reached if the percent of electric cars on streets is 55% out of the total amount of vehicles, and the accomulated annual car mileage is about 15,000 km. Furthermore, it is proposed to extend and improve the INSPIRE generic conceptual model by including those indicators into it.

Keywords: spatial data infrastructure, sustainable development, urban metabolism, geodatabase, INSPIRE directive.

1. INTRODUCTION

Globalization processes continuously change the landscape of human living environment and affect climate change. Urban environment is considered as complex physical-ecological-anthropogenic system. The human interaction with environment leads to its anthropogenic change. Sustainable development requires better understanding, modeling and knowledge (Fujiwara, et al., 2005).

Sustainable development includes sustainable economic development, strategy for effective environmental management, greening of economic activities, social aspect and territorial development (Giddings, et al., 2002). Integrity of spatio-temporal data is considered as crucial performance of urban monitoring system.

Policy-makers and city planning need flexible responsive geospatial decision-making system, not just geographic information system. Such system is built upon the corresponding spatial data infrastructure (SDI) (Karpinskyi, et al., 2016).

In Ukraine, there is a number of relevant nationwide databases which are owned by different state and private organizations. Unfortunately, there are many various incompatible data formats. It is considered as a significant barrier for information exchange between policy-makers (Lobanov, 2014; Tsvetkov, 2015).

Cities are major consumers of natural resources and sources of waste. An effective decision-making is impossible without high quality truthful and credible data, which would allow:

- To evaluate the efficiency of energy consumption, material resources and waste disposal,
- To estimate urban and regional greenhouse gas emissions, and
- To assess the quality of city planning programs and activities for developing projects for low-carbon neighborhoods and recriation zones in cities.

Starting with a review of the EU INSPIRE SDI standards, we further discuss what are their limitations in the present Ukrainian landscape. Modelling of material and energy flows of urban environment, we'll introduce novel indicators of the efficiency of domestic urban methabolism. Futhermore, such modelling would improve and enhance the exisiting SDI of the Ukrainian city's GIS platform. Legal acts of this nationwide platform are under the development.

2. LITERATURE REVIEW

The problems of sustainable urban development are studied by various theories of the rational use of socio-ecological and economic resources. Examples of such theories are the theory of urban growth machines (Bedash, 2012), the theory of agglomerations (Schumpeter, 2011), the theory of urban management (Trubina, 2011), the theory of urban ecology (Bookchin, 2005) and others. High-speed internet, cloud computing, big data, mobile devices, unmanned aerial systems, and geospatial technologies are modern technological tools. Their using for solving the problem of sustainable development of the city seems to be very effective (UN-GGIM, 2015b).

The necessity to create spatially oriented ecological models is considered by Davis, et al. (2011). They highlight an importance of geographic information to support research on sustainable development. The authors (Czerwinski, et al., 2017; Abramic, et al., 2017) analyze how the development of spatial data infrastructure in Europe (INSPIRE) can improve an efficiency of data management as well as integrate information from different society socio-technological activities. It means, for example, that data on the transport field, air quality, public health, level of environmental biodiversity are integrated into one information base. In (Martins, 2010) the issues of data organizing and managing are considered, which are taken into account when compiling geoinformation models of the concentration of pollutants in the air, as well as for assessing air quality in Portuguese cities in accordance with requirements of the National Geographic Information System. This paper emphasizes an important role of GIS due to a large amount of geographic data required for decision-making in the framework of national air quality assessment and ensuring sustainable development of urban environment.

(Scott & Rajabifard, 2017; Hasanova, et al., 2019) emphasize the role of geospatial information for monitoring 17 sustainable development goals and 169 subtasks as defined by the UN.

Based on the above brief analysis of researches, the following conclusion can be drawn. A visible obstacle to effective city governance to achieve sustainable development is the lack of geospatial information structuring. This is especially significant when operating with data, which characterize human interaction with an environment.

3. GEOINFORMATIONAL MODELS OF SPATIAL DATABASE OF SUBSTANCIAL-ENERGY FLOWS OF URBAN ENVIRONMENT

Relationship between urban environment and energy. A development of city and its energy consumption have a direct relationship. Today we can see a fast urbanization process. It leads to increase a housing stock and energy consumption.

The most of world's final energy consumption is concentrated in human settlements. It represents over 70% of the total energy consumption. Thus, more than two-thirds of total energy consumption needed to sustain cities goes towards generating global CO2 emissions (Acebillo, 2013).

Increasing concentration of GHG (greenhouse gas) leads to gradual climate change. This is confirmed by findings of Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014).

Under these conditions, decisive action is needed to limit trends in fossil fuel consumption. Taking into account the current condition of economy and the development of technologies, it is required to increase the efficiency of material and energy exchange with an environment. This will reduce a global environmental impact and dependence on fossil fuels. This approach will improve a balance between urban productivity (quality of urban life) and a constant depletion of natural resources. This ratio is expressed in fact that the socio-economic component of city should ensure GDP growth without deteriorating environmental conditions.

To mitigate the consequences of primary energy consumption and increase the anthropogenic impact on urban environment, experts in the field of municipal management are developing plans for adapting consequences of anthropogenic loads on environment. In addition, measures are being developed to save energy, to stimulate development, to significantly increase and expand recreational areas.

It is assumed that plans and activities developed by the municipal authorities will have a positive impact on condition of urban environment. However, it is not yet known how and to what extent these activities may affect the overall resilience of city. For example, some scenarios for planning and managing sustainable development may be reasonable and optimal for one city, but completely counterproductive for another one.

Energy flows and metabolism of urban environment. Modern cities are infinitely heterogeneous and changeable. The heterogeneity of city can be most accurately expressed through some metaphors. In papers (Morgan, 2011; Barter & Russell, 2013) devoted to relationship between metaphors and urban studies, the following metaphorical definitions are given: functional city, smart city, connected city, slum city, tourist city, science city, capitalist city, flexible city, toxic city, globalized city, polarized city. Such metaphors allow us to highlight the most concentrated problems and features of cities in terms of management and decision-making.

All problems and features of city life are united by the concept of modern large city, based on a paradigm of metabolism. Metabolism is understood as various forms of interaction of material, energy, human and natural components and systems of urban environment (Yanitskiy, 2013).

Over the past decades, a concept of urban metabolism has become dominant in a search for the most effective operational regulation of energy flows and flows of material resources in cities. As researches have shown (Codoban & Kennedy, 2008; Giordano, et al., 2014; Kennedy, et al., 2015), a metabolic analysis of urban environment can become a toolkit for improving science-based urban planning decisions. As a result, the efficiency of use of natural resources is increased and the degradation of environment is reduced. In addition, it becomes possible to assess the environmental impact of energy flows, materials and waste, which, in turn, allows us to localize problem areas that need increased attention.

Urban morphology is directly related to the efficiency of urban metabolism. Urban infrastructure has a significant impact on ecological footprint of population (Patrakeyev, at al., 2017). For example, electricity consumed in Ukrainian cities is generated mainly with using primary fossil fuels (coal, oil, gas, uranium). Meanwhile, the energy sector of European Union countries is focused on intense using of renewable natural resources.

The transformation of urban morphology changes a behavior of citizens, improving a quality of urban metabolism. Thus, a density of cities affects types of private and public transport used. The logistics of trade services for population in the city has a significant impact on exchange of energy in transport subsystem of urban environment. A concept of urban metabolism is shown in Figure 1 (Minx, et al., 2011). It consists of three main components: (1) sources of material and material flow from environment, (2) flow of material and energy losses of urban environment and (3) flow of productivity. It is the flow of productivity that ensures livelihoods of population and functioning of urban economy.

The metabolic concept plays an important role in movement of city from a resource-intensive consumer and a source of environmental pollution to a synergistic self-organizing system. Thus, monitoring and management of material and energy exchange is a key to sustainable development of urban environment in future. As we can see, our future is increasingly urbanized. The relationship between sustainable development and metabolic efficiency of urban environment is shown in Figure 2.

We distinguish between three factors that determine metabolic flows of urban environment. These factors are planning an urban environment, features of city morphology and quality of population life. All these factors and their components can become the driving forces of sustainable development of urban environment. Thus, as it's defined in paper (Minx, et al., 2011), determining questions in research of urban metabolism efficiency are the features of spatial organization of urban environment and lifestyle of population.

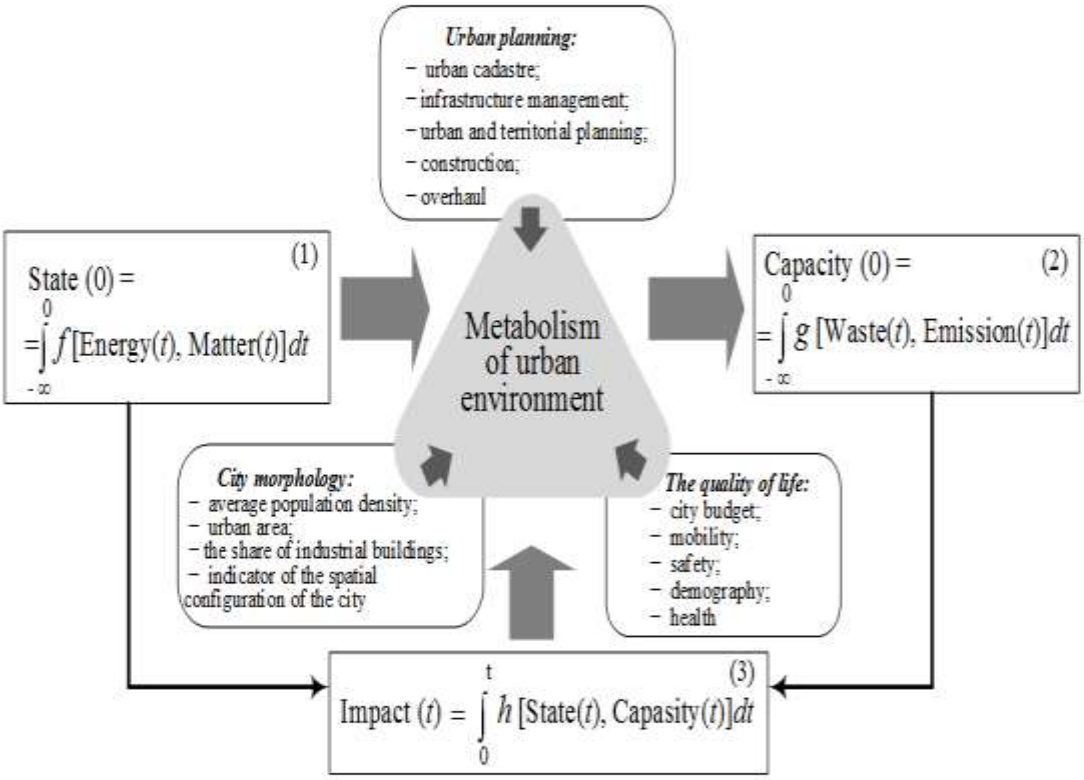


FIGURE 1 - CONCEPT OF URBAN METABOLISM (MINX, ET AL., 2011).

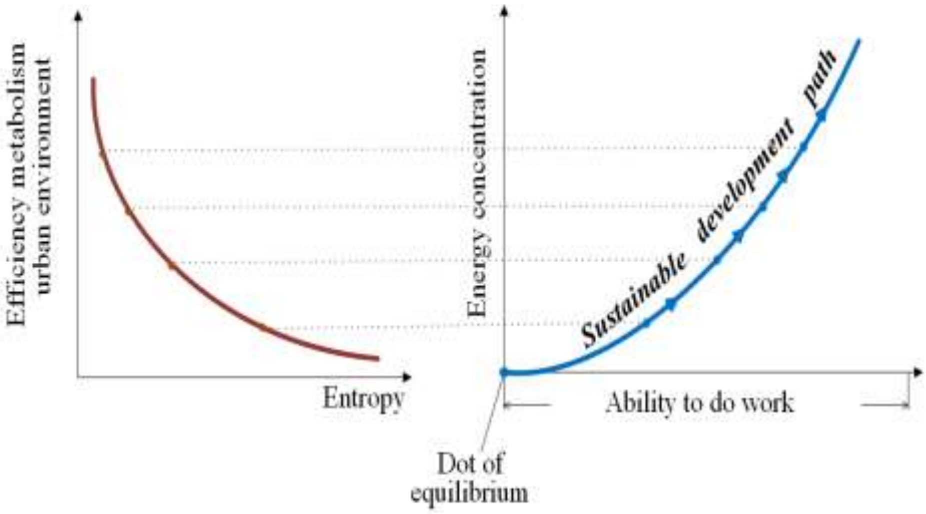


FIGURE 2 - RELATIONSHIP BETWEEN SUSTAINABLE DEVELOPMENT AND METABOLIC EFFICIENCY IN URBAN ENVIRONMENT

A system formation for geoinformational monitoring of urban environment development largely depends on availability of spatial database. The presence of such base allows exchange of data using a unified system of interdepartmental electronic interaction. To use this unified system, measures must be taken that relate to sharing of interoperable spatial data, as well as network services and technologies. These measures comply with requirements of INSPIRE directive (INSPIRE, 2007).

Information model of metabolism of transportation subsystem of urban environment. Let us consider content and relationship of indicators of material-energy flows using an example of transportation subsystem of urban environment (TSUE). The transportation subsystem ensures a spatial mobility of population and its multimodal movements. In addition, TSUE characterizes the amount of energy spent on spatial mobility, the amount of CO2 and other pollutant emissions. TSUE metabolic information model (Patrakeyev, et al., 2020) is shown in Figure 3.

We know a law of conservation of energy is one of fundamental laws of nature. Meanwhile, this law also underlies a sustainable development of socio-economic system.

In accordance with a law of conservation of energy flow (power) a change in total power of system is controlled by changing in effective power and power losses (Bolshakov, 2002; Bolshakov & Kuznetsov, 2013):

$$N = P + G,$$

where $N = \frac{dE}{dt}$ – apparent power or energy flow at the entrance to system;

$P = \frac{d\mathrm{B}}{dt}$ – net power output or stream of convertible energy, which characterizes productivity of system;

$G = \frac{dA}{dt}$ – power losses, a flow of bound energy, which characterizes level of entropy processes in system.

To monitor and evaluate the effectiveness of metabolic processes in TSUE, it is proposed to use a system of indicators of material-energy flows (MEF). These indicators are based on data from state statistical records, as well as on results of empirical data obtained from monitoring researches. The MEF indicator system is based on the power invariant. The system characterizes technological, environmental, economic opportunities of TSUE. We distinguish (see Fig. 3) indicators of potential (1-4), productivity (5-7) and missed opportunities (8-12) of TSUE.

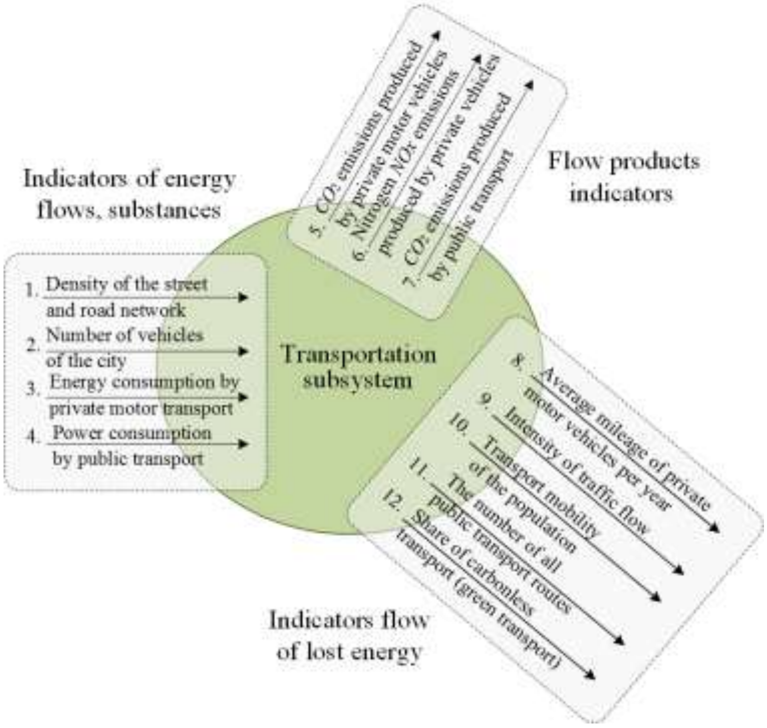


FIGURE 3 - INFORMATION MODEL OF METABOLISM OF TRANSPORTATION SUBSYSTEM OF URBAN ENVIRONMENT

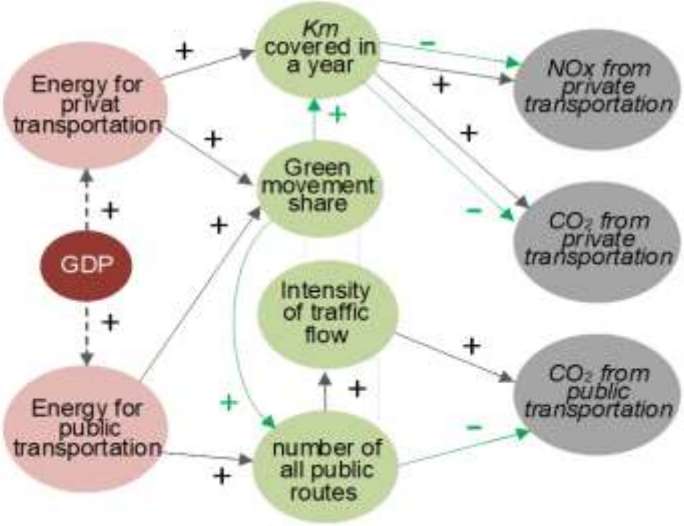


FIGURE 4 – SIMPLIFIED MODEL OF LOGICAL CONNECTIONS BETWEEN MEF INDICATORS OF TRANSPORTATION SUBSYSTEM OF URBAN ENVIRONMENT

A simplified model of logical connections between MEF indicators of transportation subsystem of urban environment is shown in Figure 4. As you can see on the figure, indicators are connected by cause-effect relationships. For example, increasing in traffic volume leads to increasing in both CO2 and NOx emissions. Sustainable development scenarios aiming at improving urban metabolism should take into account these causal relationships.

A change in value of one indicator (for example, a percentage of using of "green transport") affects each indicator that is in a causal relationship. At the same time, causal relationships are distributed throughout entire system of MEF indicators of urban environment. Analysis of causal relationships between MEF indicators allows us to select such control actions that will provide a maximum target function. In our case, this target function is a metabolic efficiency of urban environment.

Geoinformational data models for assessing trends in urban metabolism. INSPIRE Program (INSPIRE, 2007) is an initiative of European Commission. The program is based on understanding of necessity to integrate national efforts in creation of SDI within common European information space. The most of European national spatial planning and urban cadastre systems are based on using of international basic standards ISO 19100 series Geographic Information / Geomatics.

The bases for standardization of geoinformation data models for urban metabolism assessing are object classes. In accordance with requirements of ISO 19110 standard, a development of object classes allows us to present a unified system of classification and coding of data model objects for urban metabolism assessing at the conceptual level. This standard defines object classes with their names, semantics, attributes, domains and associations between object classes. Moreover, each association is described by name and roles of interacting classes in the association (Lyashchenko & Cherin, 2011).

Currently INSPIRE proposes to register and describe a relationship between urban system and environment in physical terms. This is analogous to accounting for material flows in economy of European Union Statistical Office (Eurostat, 2001).

Key issues in research of city metabolism are recognition of trends in metabolic flows, as well as an identification of relationship of these flows with spatial structure of city. INSPIRE standard recommends an approach whereby urban flow indicators reflect a physical metabolism of city in five dimensions: energy, climate change, water, waste and land use. It is proposed to obtain land use data for European cities based on Urban Atlas project. It collected here data for large urban areas, where more than one hundred thousand inhabitants live. Meanwhile, Eurostat databases and material flow accounting methodologies, according to INSPIRE standards, are not specific and do not allow answering the following three questions:

1. How can a productivity of urban system and impact of city on environment be measured?
2. What indicators characterizing total, useful power (productivity) and power losses should be systematically recorded and described in physical terms?
3. How to combine indicators of total, useful and power losses to general indicator of city efficiency?

It is difficult to answer these questions, especially because of an extremely heterogeneous nature of variables that describe an urban system.

The authors propose data models that extend INSPIRE profiles with information not yet included in specifications today. Moreover, our models are designed in compliance with rules of Generic Conceptual Model (INSPIRE Generic Conceptual Model).

The authors have developed and systematized Catalog of MEF indicators as information objects with attributes and methods based on information model of metabolism of transportation subsystem (see Fig. 3).

Formally, by an indicator we mean a collection of sets:

$$I = < N, P, M_{CL}, M_{MS}, X > \ ,$$

where N – a name of indicator;
P – indicator purpose;
M_{CL} = $\{m_{cl_1}, \dots, m_{cl_i}, \dots, m_{cl_k}\}$ – set of methods for indicator calculating;
M_{MS} = $\{m_{ms_1}, \dots, m_{ms_j}, \dots, m_{ms_h}\}$ – set of methods of indicator measuring;
X = $\{x_1, \dots, x_i, \dots, x_k\}$ – set of empirical indicators obtained using measurement methods.

For example, **ConsumEnergyByPrivatTrans** object class contains following attributes:

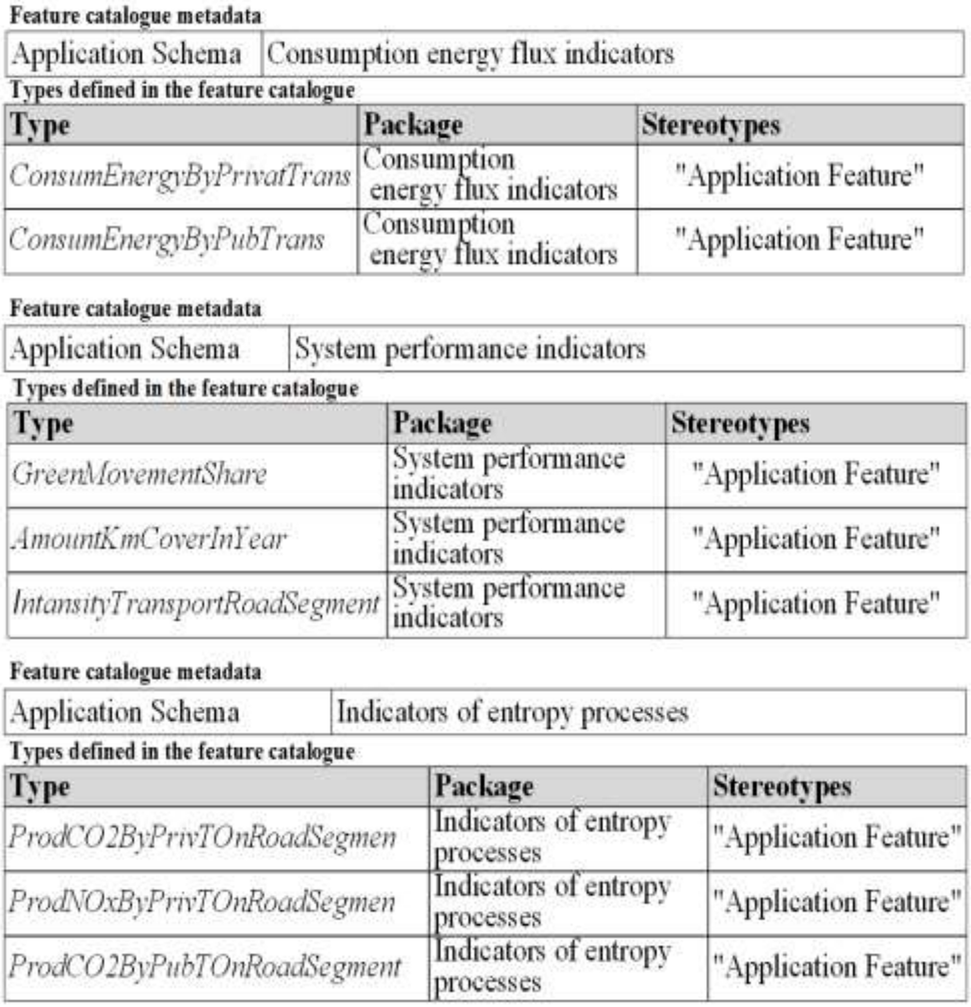
vehiclePrivatType – type of private vehicle;
numberOfVehiclePrivatType – number of vehicles of this type;
urbanDrivingCyclePrivatType – medium urban cycle by personal transport cars;
amount*Km*CoverYear – average mileage by private vehicles per year;
averConsumEnergyPer*Km* – average energy consumption per kilometer.

Given attributes of class of objects model flows of energy consumption by private transport depending on transport infrastructure of urban planning system. The class method implements an indicator calculation algorithm based on measured or received primary indicators. The method is implemented in general-purpose programming language Python in GIS environment ArcGIS 10.2. An example of the method implementation is given below:

```
import arcpy
A = arcpy.da.SearchCursor(urbanDrivingCyclePriType)
B = arcpy.da.SearchCursor(amountKmCoverYear)
C = srcpy.da.SearchCursor(numberofVehiclePrivateType)
H = overCorsumEnergyPerKm
for row in B:
   b.append(row)
for row in C:
   c.append(row)
for x in range(Dlina1):
   A = (b[x]/365)*c[x]
   row = A.newRow()
   A.insertRow(row)
for row in H:
   h.append(row)
for row in A:
   a.append(row)
for x in range(Dlina2):
   I = a[x]*h[x]
   row = I.newRow()
   I.insertRow(row)
```

An example of fragment of Catalog of indicators of material-energy flows of transportation subsystem of urban environment is shown in Figure 5. A structure of developed catalog of objects is focused on energy costs and environmental consequences caused by demand of population for various types of transport. A composition of classes of objects, which necessary to describe a mobility of population and its environmental consequences is shown ibid. Proposed classes of objects of applied data scheme allow us to describe an information model for metabolism assessing of transportation subsystem in terms of material-energy flows.

UML diagram of developed applied schema of data model for assessing a metabolism of transportation subsystem is shown in Figure 6. Here, object classes in accordance with D2.8.I.7 INSPIRE Data Specification on Transport Networks are marked in yellow, and object classes of proposed applied data model scheme for metabolism assessing of transportation subsystem are marked in blue.



Feature catalogue metadata

Application Schema	Consumption energy flux indicators

Types defined in the feature catalogue

Type	Package	Stereotypes
ConsumEnergyByPrivatTrans	Consumption energy flux indicators	"Application Feature"
ConsumEnergyByPubTrans	Consumption energy flux indicators	"Application Feature"

Feature catalogue metadata

Application Schema	System performance indicators

Types defined in the feature catalogue

Type	Package	Stereotypes
GreenMovementShare	System performance indicators	"Application Feature"
AmountKmCoverInYear	System performance indicators	"Application Feature"
IntansityTransportRoadSegment	System performance indicators	"Application Feature"

Feature catalogue metadata

Application Schema	Indicators of entropy processes

Types defined in the feature catalogue

Type	Package	Stereotypes
ProdCO2ByPrivTOnRoadSegmen	Indicators of entropy processes	"Application Feature"
ProdNOxByPrivTOnRoadSegmen	Indicators of entropy processes	"Application Feature"
ProdCO2ByPubTOnRoadSegment	Indicators of entropy processes	"Application Feature"

FIGURE 5 – FRAGMENT OF CATALOG OF INDICATORS OF MATERIAL AND ENERGY FLOWS OF TRANSPORTATION SUBSYSTEM OF URBAN ENVIRONMENT

The applied data model schema includes 8 classes of objects that represent information models of MEF indicators of transportation subsystem of urban environment. Each class from 8 object classes is classified into three sets of object classes that characterize potential, real and missed opportunities of TSUE.

To calculate an integral indicator of TSUE metabolic efficiency we use a knowledge base that implements Takagi-Sugeno-Kang inference algorithm. This approach is discussed in detail in papers (Giordano, et al., 2014; Patrakeyev, et al., 2017).

Management Expert System is based on knowledge base rules. The system calculates an index of metabolic efficiency and offers certain scenarios for development of urban environment.

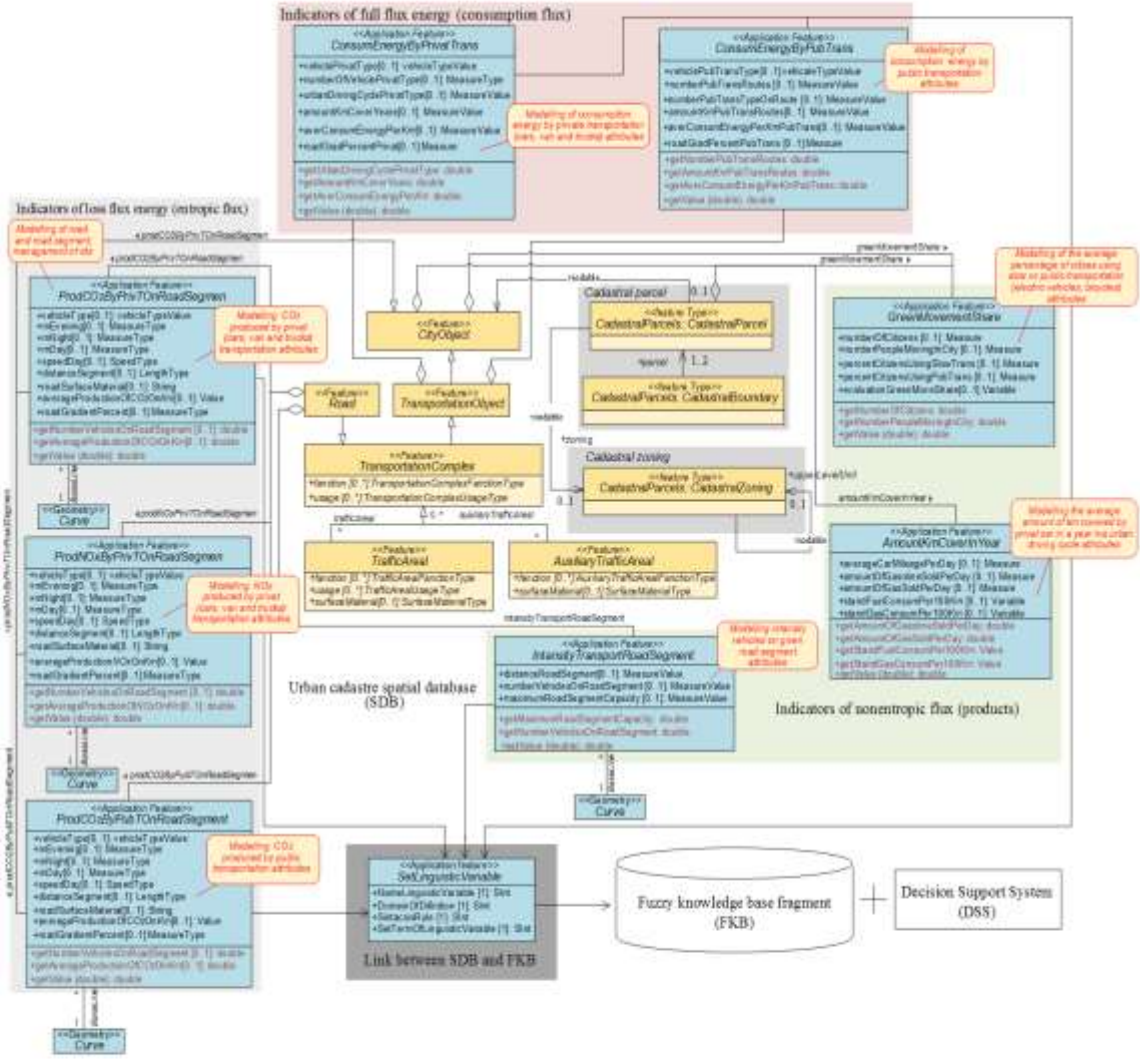


FIGURE 6 – UML DIAGRAM OF APPLIED SCHEMA OF DATA MODEL FOR METABOLISM ASSESSING OF TRANSPORTATION SUBSYSTEM

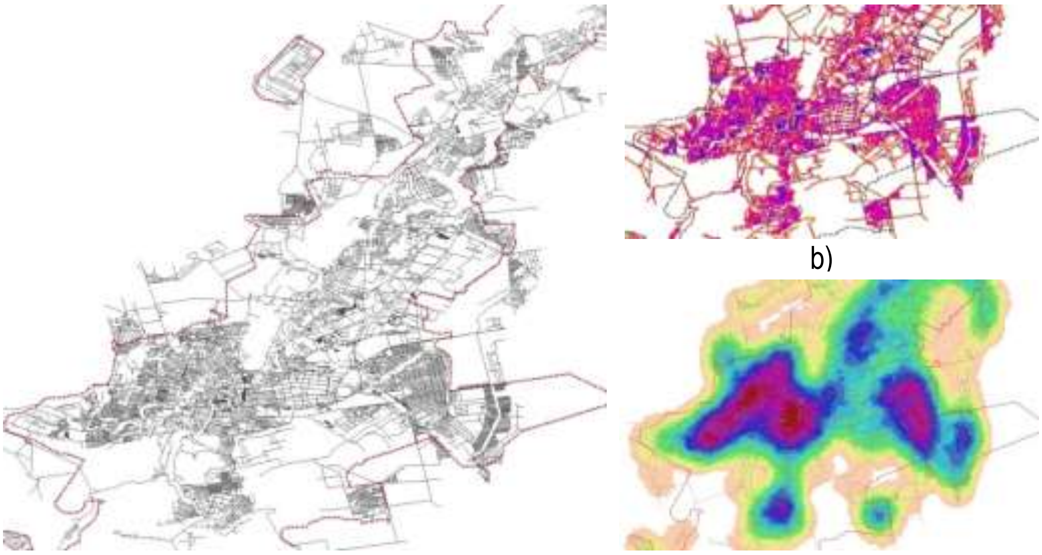
Technological issues of complex interaction of spatial database, knowledge base and decision-making system are detailed in paper (Patrakeyev, et al., 2020).

4. DISCUSSIONS

The developed applied data model makes it possible to systematically record indicators of energy flows and assess productivity in terms of metabolism efficiency of transportation subsystem of urban environment.

Figure 7 shows a structure of road network, its density and CO_2 emissions. These three figures provide an example of spatially distributed structure, metabolic efficiency of which is estimated based on twelve indicators discussed above.

This indicator of metabolic efficiency is used to build scenarios for managing sustainable development of urban environment as a whole. This strategy will allow us to choose the most optimal scenario for stability increasing of transportation subsystem.



b)

a) c)

Figure 7 – Structures of road network (a), density of road network (b), areas with the highest CO_2 production by private vehicles in Krivyi Rih city

A surface that can be interpreted as a landscape of efficiency of transportation subsystem of Krivyi Rih city for scenarios that include changes for selected space of variables is shown in Figure 8. This surface can be considered as a representation of potential capabilities of transportation subsystem of urban environment depending on change in two variables. In Figure 8 we can visually assess how a metabolic efficiency depends on degree of using of green vehicles and average car mileage per year.

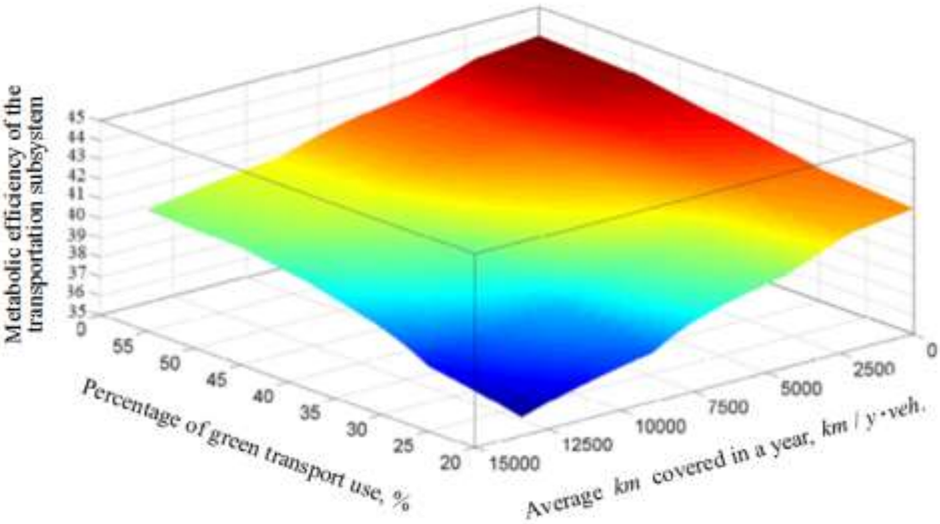


FIGURE 8 – DEPENDENCE OF METABOLISM EFFICIENCY OF TRANSPORTATION SUBSYSTEM ON TWO VARIABLES

The considered method allows us to choose one or another space of variables at the initial stage. And then, we get opportunity to evaluate metabolism efficiency. In addition, it is possible, for example, to determine in which functional zones (within boundaries of one city) metabolic efficiency indicators are similar. Moreover, it is possible to determine various scenarios for the redistribution of consumption of natural resources to increase metabolism efficiency. At the same time, you can do this without additional economic, environmental and social costs.

It is clear that an urban environment is a complex, self-regulating and open system. Adequate model developing for such system is challenging. Meanwhile, presented applied data model can be used to obtain a new perspective on sustainable development of urban environment.

5. CONCLUSIONS

The science of sustainable development is based on real world laws. One of these foundations is power conservation law. This law is that for any transformations of systems that open for energy flows (including the urban environment) a power value must be preserved. The quality and condition of urban environment are factors of sustainable development of municipalities.

To ensure sustainable development of urban environment, it is necessary to have data on flows of materials and energy. For this purpose, these data should be integrated into one information base.

These spatial data must comply with goals of sustainable development of Ukrainian cities. Meanwhile, at present, disadvantages of organizing spatial data are incompleteness of attribute data, inconsistent categorization, a lack of spatial relationships between datasets for various stakeholders and unreasonable prohibition of access to part of required data.

We have developed structures of applied data model schemes that provide an assessment of urban environment metabolism in terms of indicators of material-energy flows. Moreover, this development is based on INSPIRE requirements.

INSPIRE compliance ensures data harmonization and standardization of data using in different subject areas. These areas are transport, urban economy, impact on public health, socio-economic development of city, using of renewable natural resources and others.

Last but not least, adaptation of developed applied data models to EU INSPIRE Directive will provide more effective support for management decisions. This is a step towards improving indicators in the field of sustainable development of Ukrainian cities.

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