Municipal Waste and City Size

Subjects: Urban Studies
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By 2050, the world population is expected to reach 9.7 billion, almost 90% of which will live in urban areas. With such a fast growth in population and urbanization, it is anticipated that the annual waste generation will increase by 70% in comparison with current levels, and will reach 3.40 billion tons in 2050. A key question regarding the sustainability of the planet is the effect of city size on waste production.

Keywords: municipal waste ; city size

1. Background

Urbanization is the hallmark of the 21st century, which is characterized by tremendous demographic changes and a rapid development of urban areas and the built environment on a large scale. Most of the future population growth in the remaining part of this century will occur in urban areas. The increase in global waste production due to population growth and wealth will have a significant impact on the sustainable development of cities.

The world produces 2.01 billion tons of municipal solid waste each year, with at least 33 percent not being managed in a safe way for the environment. All over the world, the amount of waste generated per person per day averages 0.74 kg but varies widely from 0.11 to 4.54 kg. Although they constitute only 16 percent of the world's population, high-income countries (high-income countries—78 countries with GDP above 12,000 $/year) generate about 34 percent, or 683 million tons, of the world's waste [1][2].

Considering the fact that urban populations will have increased by 2–3 billion by the end of the 21st century, understanding the way in which the size of cities affects the municipal waste volume can provide us with an insight into how city size can be part of a larger regional or national strategy for waste reduction [3].

2. The Importance of Scale for the Production of Municipal Waste

Galileo developed the idea of allometric growth in his treatise 'Discorsi e demonstrationi matematiche, intorno a due nuove scienze', which was published during his house arrest in 1638 [4]. He noticed that the bones of larger animals grew thicker at a faster rate than they grew in length compared to the same bones in smaller animals. Thus, the height-to-circumference ratio decreases along with the animals' growth.

Therefore, what is 'scaling'? In its most elementary form, it simply refers to the reaction of the system when its sizes change [5].

Scaling characterizes the way a given system quantity, *y*, depends on the size of the system. The scaling law is shown in the form of the following exponentiation relation:

$$y = ax^b \tag{1}$$

where *x* is the linear size of the system and *y* is its measure, whereas a is the proportionality coefficient, and *b* is the exponent specifying the exponentiation law.

The scaling laws apply to both natural phenomena and those resulting from human activity [5].

In particular, the scaling laws refer to models of spatial organization of cities and their growth—a well-known example of a scaling relation is 'Zipf's Law', which states that a city's population decreases inversely with its rank among other cities in the same city system [6] (Zipf's Law or Estoup–Zipf's Law—the law that describes a frequency principle of using individual words in any language. Zipf's law was mathematically expressed in Zipf's equation: r × f = constans, where: r is the rank of a word in a text or a group of texts, and f is its frequency of occurrence. [6]).

Cities offer benefits resulting from the economy of scale. Concentrations of people, large-scale infrastructure, and economic activities enable innovation and efficiency. Recent studies have shown that cities may exhibit different types of scaling in different urban phenomena or properties [7]. Nonlinear scaling (when exponents take a value less than 1) resembles the parallel allometric scaling laws observed in living organisms, and represents the benefits of the scale resulting from the increase in efficiency by sharing infrastructure; it is exposed, inter alia, in electric networks (by the length of electric cables) and road systems (length of roads or amount of road surfaces). Superlinear scaling (when the exponent b is greater than 1) seems to be unique to social systems, and is connected to the concept of network effects which lead to human ingenuity and creativity. Superlinear scaling has been identified in the number of new patents, inventors, research and development, employment, total salaries, etc. Linear scaling (when the exponent b is approximately equal to 1) means a proportional increase in urban phenomena/measures along with the size [8].

The size of a city's population, as well as its spatial organization and structure, can influence the amount of waste. Data from cities around the world suggest that climate, technology, density, and wealth are important determinants of waste generation.

The subject of the research is to establish allometric dependencies between the size of a city and the production of municipal waste in 930 Polish cities. The results show that this dependency varies across cities of different size, area, population density, and per capita income. In analogy to Kleiber's law [9] (Kleiber's Law, named after Max Kleiber because of his biology in the early 1930s, is based on the observation that, in most animals, the metabolic rate increases to ¾ of the strength of the animal's weight [9]), the amount of municipal waste, along with the increase in the city's population, should decrease due to the benefits resulting from the use of the understood service and network infrastructure of cities, which, in many cases, obeys the law of allometric growth. Are larger cities more economical in terms of waste production than smaller cities? Moreover, it is important to determine the importance of the city's basic spatial and economic indicators, i.e., area, population density, or GDP per capita for municipal waste produced. The knowledge of these relations can be fundamental to the optimization of the size of waste collection and processing facilities in cities.

3. Universal Quantifiable Features of Cities

Parysek [10] claims that, since the formulation by Ludwig von Bertalanffy [11] of the general theory of systems, it has been increasingly used in determining the subject of research in various fields of knowledge. The systemic approach to the subject comes from biology, where systems are living organisms. He further states that, by analyzing the spatial and functional structure of the city, we can conclude that the organism is an adequate model for the city system.

In a city, as in any living organism, there is a conversion of matter and energy. It is a specific form of metabolism, consisting not only of the consumption of various forms of energy of materials, but also of capital flow, knowledge, skills, information, etc. This form of metabolism can be identified with urban metabolism and, similarly to living organisms, can be studied using the scaling law [12]. Organisms, as metabolic engines, are characterized by indicators of energy consumption, growth rate, body size, and lifetimes, and therefore have a clear reference to urban systems [13][14]. Bettencourt states that cities manifest remarkably universal, quantifiable features. As to be expected, "size is the major determinant of most characteristics of a city; history, geography and design have secondary roles" [8][15][16].

The basic discoveries of allometric relationships describe the relationship between the total area of a city and its number of inhabitants [17][18][19] and the relationship between the city's area and the total length of its borders (fractal nature) [20][21]. Other relations concern the relationship between the city's surface and the total surface of its roads [22].

Kennedy [23] and others have quantified the energy and material flows across 27 megacities worldwide with a population of over 10 million people since 2010. It was confirmed that the flows of resources and waste generation across megacities largely follow the laws of scaling.

Few studies have investigated the scaling performance of solid waste disposal through statistical analysis with empirical data. Pan, Yu, and Yang [24] tested a sample of 651 cities in China using a correlation analysis and grouping model that determined the characteristics and overall trends of solid waste generation in five city groups of varying scales between 2007 and 2016.

Kleiber's law of allometry says that the metabolic rate is based on body weight with an exponent of 0.75. It should be assumed that the elimination of waste from the body is a system proportional to the metabolic process, that is: the more metabolic waste is produced, the more metabolic waste must be excreted [25]. Similarly, in an urban "organism", the amount of waste generated should be scaled to the number of inhabitants (or other city parameters) with an exponent of 0.75.

4. Municipal Waste Problem

Waste collected by or on behalf of municipalities includes household waste originating from households (i.e., waste generated by the domestic activity of households) and similar waste from small commercial activities, office buildings, institutions such as schools and government buildings, and small businesses that treat or dispose of waste at the same facilities used for municipally collected waste [26].

The amount of generated municipal waste depends on many factors, of which the most important are life standard, population rate, and goods consumption scale and intensity.

Municipal solid waste is remarkably diverse in terms of physical and chemical composition. It mainly depends on the equipment of buildings with technical and sanitary devices (mainly the heating method), the type of buildings, and the living standards of the inhabitants. Most often, municipal waste contains approx. 40–50% of organic substances, approx. 50–60% are mineral parts. Waste composition in the OECD region (The Organization for Economic Co-operation and Development (OECD) is an international organization that works to build better policies for better lives. It counts 37 member countries that span the globe, from North and South America to Europe and the Asia-Pacific.) is slightly different due to high income, and for organic waste it is below 30% [27].

The components contained in municipal waste, mainly organic, undergo biochemical changes, and affect the environment through decomposition products: carbon dioxide, ammonia, hydrogen sulfide, methane, nitrates, nitrites, sulphates, and others.

Municipal waste he poses a threat to the environment due to the possibility of the contamination of air, groundwater, and surface water with pathogenic microorganisms, for which it is a medium [28]. Solid muncipal waste varies greatly in terms of physical and chemical composition.

Based on the volume of waste generated, its composition, and how it is managed, it is estimated that 1.6 billion tons of carbon dioxide (CO_2) equivalent greenhouse gas emissions were generated from solid waste treatment and disposal in 2016, driven primarily by open dumping and disposal in landfills without a landfill gas capture system. This is about 5 percent of global emissions. Solid waste-related emissions are anticipated to increase to 2.6 billion tons of CO_2 equivalent per year by 2050 if no improvements are made in the sector [2].

In the European Union (EU), the amount of municipal waste generated per person in 2018 amounted to 492 kg, 5% less compared with its peak of 518 kg per person in 2008. In total, 220 million tons of municipal waste were generated in the EU in 2018, and this was slightly higher than in 2017 (218 million tons). With 766 kg, Denmark generated the most municipal waste per person among the EU Member States in 2018. At the other end of the scale, Romania generated 272 kg of municipal waste per person in 2018 and Poland generated 329 kg per person [29]. There was a perceptible change in trends in municipal waste management in the EU-28, with an apparent shift from disposal methods to prevention and recycling. Less waste is being landfilled because of reductions in the generation of some wastes and increases in recycling and energy recovery. Municipal waste landfilled decreased by almost 43% [30], but still corresponded to about 3% of total EU greenhouse gas emissions [31].

The correlation analysis of the population in the individual EU countries and the total volume of municipal waste and volume of waste per capita and GDP per capita in 2018 indicates that, in the first case, the Pearson coefficient (Rp) is 0.98, and 0.60 in the second (28 countries with the UK). The coefficients of determination (Rp^2) are 0.97 and 0.52, respectively, which proves that the correlation model in the first case is very good and works 97%, and in the second case it is worse and works 52%.

In the case of Poland, a detailed analysis of the relationship of GDP per capita to the volume of waste per capita indicates that Poland produces much less municipal waste in comparison with other EU countries with a similar GDP per capita.

The question about the reasons for such a phenomenon, in view of the insufficiently developed waste management infrastructure in Poland, remains unanswered and requires further research.

In 2018, the European Commission (CE) presented the amended content of the Waste Framework Directive, setting new targets for increasing the reuse and recycling of municipal waste to a minimum of 65% by 2035. [32].

In the face of the growing amount of municipal waste generated in European countries in recent years, it has become especially important to search for sustainable methods of municipal waste management. CE activities in waste management are recommended based on the ReSOLVE framework (regeneration, sharing, optimization, loop, virtualization, and replacement) [33] (The ReSOLVE framework was developed by the Ellen MacArthur Foundation and

McKinsey, which are important bodies in the development of tools supporting the transformation process towards a circular economy in the EU. The circular economy has been described as a concept that mimics living systems. A helpful reframing, consistent with a circular economy approach, is to think of cities as living systems that rely on a healthy circulation of resources [33]).

It should be noted that in the European Union legislation on new urban waste management programs, there is no direct reference to urban planning issues, for example, regarding elements of city infrastructure, city area, or population density.

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