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Methodology of a Circular Economy in a Specific Territory

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Abstract: This article refers to the UN Sustainable Development Goals (SDGs), adopted in 2015 by the 193 countries of the UN General Assembly, of which Goal 12: Ensure sustainable consumption and production patterns has important implications for achieving a zero-waste, circular economy. The methodology of achieving integrated zero-waste production and a circular economy is discussed for application in a specific territory. The methodology consists of the following key aspects: (a) a targeted program of zero-waste production addressing problems concerning industrial and domestic waste in a specific territory; (b) targeted zero-waste production subprograms addressing industrial waste problems; (c) Industry 4.0 technologies involved in the development of a circular economy in a specific territory; (d) involvement of residents of a territory in collectively addressing all environmental problems and participating in zero-waste production organizations; and (e) mathematical, software, and IT methodologies of implementing a zero-waste and circular economy in a specific territory. An empirical analysis of the methodological aspects was carried out, using the example of a municipal district with a developed multisectoral economy. This study demonstrates the concept of waste classification involving the use of waste as raw material in a municipal district, including a specific targeted subprogram for recycling polymer products in a municipal district. A mathematical model of a zero-waste and circular economy program in a municipal district is depicted as an alternative graph to show different options of operation while addressing both local and global goals. An analytic hierarchy process was used to empower decision-makers to interactively select the option that best corresponds to the financial capacity of the municipal district, the duration of the program, and the technical requirements of the task.

Keywords: linear economy; circular economy; green economy; sustainable consumption; sustainable production; alternative graph for waste management

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1. Introduction

The global population is continuing to increase over time. As human needs increase, social problems arise, which tend to be resolved through economic growth. Few doubt that, in order to ensure the stable development of both an individual country and the world as a whole, economic growth should demonstrate an increasing trend. In this context, it seems unlikely that a permanent and fundamental decoupling of economic growth from environmental pressures and impacts can be achieved at the global scale [1]. Moreover, economic growth itself represents the root cause of significant environmental problems. Scientific researchers continuously emphasize that violations of the natural balance of the Earth's ecosystem are due to anthropogenic factors. These include harmful emissions of greenhouse gases and solid and liquid waste produced by industrial and agricultural systems, as well as those generated by human society. The total emissions of greenhouse gases and waste materials greatly exceed the natural ability of the Earth's ecosystem to self-purify. For example, contemporary patterns of economic activity generate approximately

300 million tons of plastic industrial waste each year. Serious environmental problems include an increase in the temperature of the lower layers of the planet's atmosphere, decreased biodiversity, land degradation, and polluted water courses. Currently, it is estimated that 0.74 kg of waste material is generated per person per day, for a total global population of 8 billion people [2]. One can only imagine how much industrial waste and civil household waste is produced under the contemporary model of economic activity, referred to as the "take, make, and waste" model, or in a linear economic model with a projected population of 10 billion people, and the corresponding impacts on the ecosystem.

Several scientific papers have been published specifically on the topic of the circular economy. The first ideas about closed economic systems were presented in the studies of the American economist Kenneth E. Boulding [3], who noted that society needs closed cycles of substance circulation because there are no inexhaustible resources on Earth. Industrial ecosystems were described by R. Frosch and N. Gallopoulos in 1989 [4]. The topic is also widely represented in the studies by McDonough, W.M. Braungart [5], Alla Petrasheuskaya [6], and Ashby, A. [7]. The activities of the Ellen MacArthur Foundation [8–11], which concentrates on the formation of a circular economy in the European Union, conducts active research and educational activities. Closed supply chains and return logistics are considered in the studies by Zuluaga J.P.S., Thiell M., Montanez, J.P. [12], Sauve, S. and Sloan [13], and Skripnuk, D.F. and Cherenkov, V.I. [14,15]. Methods for designing goods suitable for complete reprocessing are presented in the publications by Preston, F. [16], Mentink, B. [17], and Beuren, F. [18]. Firnkorn J. and Müller M. [19] also analyzed the profitability of products based on technology that fulfills the provisions of the circular economy. There are scientific articles and dissertations on the subjects of industrial ecology, the circular economy, and car-sharing [20–27].

In the course of analyzing the scientific literature, a continuous transition process of enterprises to circular economy principles was revealed. However, an approach that considers different industries combined within a single territory, which is necessarily based on the principle of closed cycles per se, is poorly represented. In particular, the stimulation of businesses and the general population to apply the principles of a circular economy within a specific territory has been insufficiently studied. Thus, there is a clear need for research into the development of new technologies aimed at closing disparate cycles of material circulation, initiating new consumption patterns, and providing methods for assessing the economic and environmental efficiency of processes applying the principles of a circular economy within a specific territory. This should also include the ideas of "green logistics", applying innovative approaches to the organization of logistics processes within the territory to minimize environmental damage. Different definitions of this term can be found in different sources; these combine economic and environmental elements, including production costs. Due to the application of green logistics, the entire production chain becomes eco-sustainable while retaining operationality. In this way, "green supply chains" can be created and coordinated within a certain territory.

The principles of a circular economy [28] within a specific territory are developed to minimize the use of the primary resources that are fed into the system, circulating products, components, and materials in the economy, which realizes their full utilization potential. Unlike the linear model, the circular model applies rigorous systems, taking into account the impact of each decision on the entire system within the territory and not just at the decision point. The principles of the circular economy within the territory consider the possibilities of how of closed systems work when brought together.

Based on reports from the Ellen MacArthur Foundation [8–11] and the above-mentioned studies, we propose the following definition of a circular economy based around an environmentally oriented system applied in a specific territory. Notably, this formulation does not describe a general concept of the circular economy, but one aimed at application in a particular territory.

An environmentally oriented system applying the principle of the circular economy in a specific territory comprises approaches to the design, production, use, and processing of goods. These aim to preserve the useful qualities of the materials by closing the life cycles of goods using an industrial symbiosis network structure. This connects industrial enterprises, organizations, institutions, and residents based on the assumption of a paradigm shift in the creation and use of goods in a particular territory, referred to as the Fourth Industrial Revolution (Industry 4.0).

From a methodological point of view, Industry 4.0 can make a significant contribution to the development of a circular economy by applying fundamental technologies such as robotics, artificial intelligence, the Internet of Things, 3D printing, cloud computing, Big Data, and 5G technology. With the rationalization of production and consumption due to the introduction of new technologies into the economic cycle, new concepts of work arise. The principles of this economic model apply to all branches of economic activity and the entire product life cycle—in particular, from the production and consumption of goods to the processing of used products and industrial waste. The efficiency of the cycle is increased due to the reduction in waste materials required to be stored, buried, or incinerated [29]. At the same time, effects can be observed in all three structural areas of the circular economy. Only by applying an integrated approach to the problem of waste, combining waste sorting, the recovery of recyclable materials, and heat recovery, can economic and environmental efficiency be maximized.

Tasks associated with an integrated approach to the problem of waste processing should be performed by automatic technological complexes that perform all stages automatically using specialized machines.

The goal of the present study is to demonstrate a methodology to achieve zero-waste production and a circular economy in a specific territory of a municipal district with a developed and diversified economy. Thus, the following tasks have to be fulfilled:

(a) Classify waste and use it as a raw material in a municipal district within a developed and diversified economy;
(b) Develop a program for waste-free production and a circular economy in the municipal district, taking the form of a mathematical model and an alternative network, as a necessary basis for the transition to a closed economy;
(c) Develop a targeted subprogram for modeling waste-free production for certain types of waste in the form of a mathematical model and an alternative network, as a necessary basis for the transition to a closed economy;
(d) Develop the information and computing network of interconnection of enterprises on the territory of the municipal district;
(e) Develop mathematical tools for choosing a solution at the stages of creating and implementing a methodology in conditions of information uncertainty: the dependence of costs on the duration and the scientific and technical level; and the selection of effective options according to various criteria.

The principles and models of a circular economy are applied within a specific territory to advance the "Common Good", as defined and regulated by the UN Sustainable Development Goals.

The information base of the present study comprises international legal acts, in particular, EU acts; statistical data from EU services and international organizations, in particular Eurostat, UN, and the Ellen MacArthur Foundation; as well as expert reports on the circular economy.

2. Theoretical and Empirical Prerequisites for Achieving Waste-Free Production and the Creation of a Circular Economy in a Specific Area

2.1. Fundamentals of Achieving Waste-Free Production and the Creation of a Circular Economy

Waste-free production should be understood as a production system that integrates the use of raw materials, fuel, and energy, as well as processes that avoid generating waste or ensure the reprocessing of all remaining production and consumption waste to obtain commercial products, the manufacture of products with characteristics that enable their reuse, and those featuring the complete absence of environmental impacts, thereby reducing economic damage from pollution [30,31].

A circular economy comprises an economic system aimed at saving money, eliminating waste, and achieving deep sustainability [32]. Achieving waste-free production and the creation of a circular economy implies a long process that will require the solution of many problems: technological, economic, organizational, psychological, and others. Let us describe the basic principles of creating waste-free industries and the circular economy, which can be gleaned from recent publications. The theoretical concept of creating waste-free industries and a circular economy involves the integrated use of raw materials, the improvement of existing technologies as well as the creation of fundamentally new ones, the creation of closed water and gaseous cycles, cooperation between enterprises, and the creation of territorial production complexes [33].

Principles for the creation of waste-free industries and a circular economy are as follows:

(a) The concept of waste-free production implies the inclusion of waste from previous cycles in the present production cycle. This refers to the mandatory inclusion of all components of secondary raw materials in production, including the maximum possible utilization of energy resources;
(b) As well as implying the inclusion of consumers in the cycle of raw material utilization, the concept of waste-free production envisages the return of products to the sphere of production following their obsolescence;
(c) Waste-free production involves the cooperation of enterprises that produce a large quantity of waste with other enterprises that can consume this waste as raw material. In other words, close cooperation between industries is required. Such close cooperation of industries is possible only at the level of the territorial–industrial complex. Waste-free production should aim towards a practically closed system in a municipality, analogous with natural ecological systems. This type of production should be based on technologies for the complex processing of raw materials, which enables the separation and processing of waste into finished products;
(d) The concept of waste-free production involves the development and implementation of waste-free technologies for reducing the anthropogenic impact of industrial waste on the natural environment to preserve normal functioning of the ecosystem. Thus, new technologies are required whose introduction would significantly reduce or virtually eliminate the generation of waste and its negative impact on the environment.

The development and implementation of waste-free industries and the circular economy is based on a number of principles, among which the principle of consistency is foremost [34]. According to this principle, each individual process or product is considered to be an element of the entire territorial–production complex in a specific territory, which also comprises an element of the ecological and economic system at a higher hierarchical level. The systemic principle underlying the creation of non-waste industries and the circular economy should take into account the growing interconnection and interdependence of natural, industrial, and social processes.

Another important factor involved in waste-free production is the complexity of raw material and energy resource use. This principle requires the optimal use of all raw material and energy components. Almost all currently used raw materials are multi-component; however, over one-third of their cost is represented by accompanying elements that can only be extracted with complex processing.

The third general principle of creating non-waste production is the cyclicality of material flows. The simplest examples of cyclic material flows include closed gas and water circulation cycles.

The fourth basic principle of creating waste-free production consists of the requirement to limit the impact of production on the natural environment. This principle is primarily associated with the conservation and reproduction of natural and social resources such as atmospheric air, fresh water, landscapes, flora and fauna, recreational resources, and public health. The implementation of this principle is ensured by a combination of effective monitoring, environmental regulations, and multi-level nature management [30].

2.2. Network Interaction Forming a Basis for Cooperation between Enterprises Generating Large Quantities of Waste and Enterprise Consumers of this Waste

Production cooperation comprises the establishment of direct links between enterprises for the joint creation and use of waste-free production technologies and the circular economy.

The network interactions of enterprises located within a municipality are represented by an information and computing enterprise interconnection network (ICEIN). An information network transmits data on technologies, processing messages, and provides access to data on technologies. The network interactions of enterprises correspond to the network model of data transmission, presented in the digital form TCP/IP [35]. The Internet protocol TCP/IP is commonly used to implement a wide range of functions: file sharing, printer sharing, and remote access to systems and servers [36].

Within the framework of the ICEIN, the following subsystems are being developed:

(a) An intersectoral scientific and technological center for comprehensive analysis and forecasting the development of waste-free production and circular economy;
(b) An information support subsystem for the methodology of waste-free production and circular economy in the municipal territory, dedicated to the collection, storage, searching, and processing of data;
(c) Subsystem of software for the methodology of waste-free production and circular economy, developing mathematical tools for choosing solutions at the stages of creating and implementing the methodology under conditions of information uncertainty;
(d) Subsystem for providing technologies of waste-free production and circular economy, i.e., the collection and development of technologies and knowledge bases formed on the basis of Industry 4.0 technologies in order to develop a circular economy in enterprises of the municipality.

The main functions of the intersectoral scientific and technological center for the comprehensive analysis and forecasting of the development of waste-free production and the circular economy are:

- Monitoring and system analysis of waste-free production technologies and the circular economy;
- Research and forecasting of the development of waste-free production technologies and circular economy;
- Assessment of waste-free production technologies and the circular economy;
- Scientific and methodological support for the development and implementation of waste-free production and circular economy technologies;
- Assessment and analysis of the impact of waste-free production technologies and the circular economy on indicators in the municipality.

2.3. Potential for the Implementation of Waste-Free Production and the Circular Economy in the Municipality

The second key principle of waste-free production and the circular economy is the mandatory inclusion in the production of all components of secondary raw materials, including the maximum possible use of energy resources. The territory of the municipality, which is characterized by a diversified economic structure, has significant potential for the utilization of secondary raw materials. By classifying waste from enterprises in the municipality from the standpoint of the use of industrial waste as secondary raw material, the diversified economic structure of the municipal territory acquires sufficient potential for the implementation of waste-free production and the circular economy.

Zero-waste manufacturing and the problem of utilizing industrial and domestic waste, which underlies the theoretical postulate of a closed economy, comprises an ambitious task facing humanity. The enormity of the problem becomes clear if we classify it from the standpoint of using industrial waste as a secondary raw material. Let us single out six main types of secondary raw materials [37]: secondary polymer raw materials, secondary wood raw materials, secondary food raw materials, secondary construction raw materials, secondary textile raw materials, and waste paper.

Let us start with recycled polymer raw materials. This type of raw material represents a waste material generated by primary processing. There are several approaches to classifying secondary polymer waste, including by complexity, the cost of disposal, and polymer types. In terms of complexity and the cost of disposal, all secondary polymer waste can be further divided into three types: polymer waste with useful properties, polymer waste with average properties, and hard-to-recycle polymer waste. The first type of polymer waste includes clean or conditionally clean production waste. This type of waste is collected in places where collection is either well established or not required, ensuring high profitability of recycling. Polymer waste with average properties includes polymer production and consumption waste that contains an acceptable level of pollution, as well as waste used in food production. This type of recycling is characterized by a reduced need for more sophisticated processing equipment involving additional costs for sorting and cleaning waste. The third type of polymer waste includes hard-to-recycle polymer waste. This type includes very heavily polluted and mixed waste, as well as waste composite materials, household waste, and automotive equipment. This type of waste, which comprises 60–85% of the total proportion of polymer waste, demonstrates low recycling profitability. The next type of classification comprises the separation of waste by polymer type. On this basis, all types of polymers can be divided into two large groups: polymer waste from the production and consumption of high-capacity and expensive engineering plastics, and packaging, furniture production, and construction waste. The first group includes low- and high-density polyethylene, polypropylene, polyethylene terephthalate, polyamides, and styrene plastics. For this type of polymer waste, there are established recycling technologies and developed markets for recycled material. The second group, generally characterized as packaging, furniture production, and construction waste, uses packaging from polyethylene terephthalate; two- or multi-layer films for food packaging; disposable tableware, packaging, and heat-insulating materials; polyurethane foam; plasticized polyvinyl chloride; and rigid polyvinyl chloride.

Secondary wood materials include waste wood from industrial production and consumption, as well as primary processing products. Industrial wood waste has several main features. The first classification feature is the type of wood processing. On this basis, wood waste can be divided into solid waste, comprising branches, stumps, roots, and soft waste. Wood dust, sawdust, and shavings are examples of softwood waste. In addition, there is green tree waste, comprising the needles and leaves of trees. Industrial and consumption wood waste can be classified according to the stages of wood processing, according to which three types are distinguished: waste produced during logging (branches, tops, stumps, and roots); waste from primary wood processing obtained during sawmilling or plywood production (shavings, sawdust, and bark); and waste from secondary processing during furniture manufacturing, including cuttings, sawdust, and shavings. Secondary raw materials obtained from wood waste can partially or completely replace primary raw materials in a number of industries [38]. Large lumpy wood waste can be used for the manufacture of small products, roof tiles, and household items. Small lumpy production waste can be used to produce technological chips employed in the manufacture of raw materials in the pulp industry. In addition, industrial wood waste is used for the manufacture of essential oils, charcoal, various types of building materials, and wood flour.

Wood waste consumption can also be classified by the manufacturing technology, purpose, and type of product. According to the manufacturing technology, wood waste consumption can be divided into carpentry, glued, pressed, molded, and wicker. Classification features also include the purpose and type of product. On this basis, all wood waste consumption can be divided into wooden houses (panel, frame, and combined), building materials (glued structures, windows, and doors), wagon and machine equipment, agricultural machinery equipment, ship equipment (supports, partitions, and hulls,) furniture products (cabinet furniture, bar furniture, and upholstered furniture), musical instruments (keyboards and bowed instruments), wooden containers (barrels and boxes), sports equipment (skis, clubs, and oars) and other products, including dishes, toys, etc. [39].

Secondary food raw materials comprise industrial and consumer food waste and products of their primary processing. All food waste can be divided into three large groups according to the place of generation: waste generated at food production enterprises, waste generated by public catering enterprises, and household waste. Food waste can also be separated into animal waste (meat, poultry, eggs, and fish) and vegetable waste (fruits, berries, vegetables, and cereals), as well as in terms of their physical characteristics. Industrial and consumer food waste can be divided into solid, liquid, and soft. Food waste can be used to produce animal feed, composted to make fertilizer, and produce energy or fuel. In terms of its hazards, this type of waste is categorized in the fourth and fifth classes, which means that it does not harm the environment [40].

Secondary construction raw materials comprise various types of industrial and consumption waste, as well as primary processing products intended for use in the production of building materials and construction. All construction waste can be divided into three broad categories. The first category of construction waste includes bulky waste that is generated either at the beginning of the construction of a building or following its demolition. The second category, comprising waste materials that are produced during construction, includes various kinds of construction waste such as packaging film and paper. The third category includes other waste produced as a result of finishing the project. In addition to the categories into which construction waste can be divided, it is necessary to consider their main types. Thus, as a result of construction, waste is generated in the form of soil and crushed stone, concrete, brick, tile and ceramics, bituminous mixtures, and mixed construction waste. Soil and crushed stone waste comprise construction materials that are removed and used during the construction process, along with fractions of concrete, bricks, and ceramics. Bituminous mixtures are waste blends remaining from the construction of road surfaces. Mixed building materials comprise various materials formed during construction. In addition, construction projects may generate waste in the form of metal products, glass, wood, and various structural elements.

Secondary textile raw materials are also distinguished among the types of secondary raw materials, comprising textile production and consumption waste and products of their primary processing. This type of waste can generally be divided into four groups. The first group of textile waste includes fibrous production waste. The processing of such high-quality waste materials into final products can be carried out without the use of additional equipment. The second group includes all types of textile waste requiring special processing methods. Such production waste must be sent to special plants to be processed for recycling. Oakum, furniture wadding, batting, and geotextiles are made from this type of recycled textile waste. The third group includes industrial and consumer textile waste which, due to the lack of special equipment or impossibility of being recycled into new products, can be used as cleaning materials. The fourth group of waste comprises low-quality production waste. This group of waste includes sweepings and fluff from dusty chambers. Low-quality textile production waste is completely unsuitable for processing into textile fiber; therefore, it can only be used for the production of various composite materials.

The last category of secondary raw material comprises waste paper, including discarded and obsolete paper, cardboard, printing products, and business papers. Waste paper is usually divided into three main categories: high-, medium-, and low-quality waste paper. High-quality waste paper includes waste from the production of white paper of the highest quality, including drawing, drafting, and writing paper, materials with minor color or black-and-white markings, paper residues made from unbleached pulp, as well as cartridge and insulating paper. Waste paper of medium quality includes production and consumption waste, including corrugated cardboard and paper not manufactured to allow printing on its surface, derivatives of white cardboard on which black and white or color printing is allowed, and any other types of white paper such as books. Low-quality waste paper includes products made from unbleached pulp, waste from cast paper production, industrial paper waste exhibiting non-moisture impregnation properties, paper with a copy layer, and mixed types, including various types of wallpaper and photosensitive paper.

Industrial and consumption waste that can be used as secondary raw material appears as a result of production activities and consumption in a particular area. Production, technological, and business processes are implemented in a specific area using particular raw materials. These include secondary polymer raw materials, secondary wood raw materials, secondary food raw materials, secondary construction raw materials, secondary textile raw materials, and waste paper. The specific territory can be a municipality, several municipalities, the territory of several companies, or the territory of any region or several regions of the country.

Different types of industrial and household waste can be used as secondary raw materials in various technological processes. Our development team was able to find ways to use industrial and domestic waste in the same area. The environment affects the quality of life; therefore, residents of the territory under consideration should be involved in tackling all ecological problems. Therefore, the organization of zero-waste production and solving problems associated with industrial waste and household waste should be addressed not only for a separate type of raw material, but in a complex for all types of raw materials based on their social use.

The formulation of this task demonstrates the importance of inter-related problems: the organization of zero-waste production, solving the problem of industrial waste and household waste, the boundaries of the territory in which such problems will be solved, z the definition of social roles when solving an area's environmental problems.

The transition from a linear to a closed economy model implies a comprehensive solution to the problems of zero-waste production and recycling of industrial and household waste by all types in a specific area. Here, it is assumed that the integration of industrial and consumption waste into new economic processes can reduce pressure on the planet's ecosystem.

Contemporary waste processing technology is used to convert several main types of waste into secondary raw materials. Thus, when wood waste is processed, three main methods are used: biological processing, mechanical processing, and chemical processing [41]. For the processing of food waste, the following are mainly used: processing by worms (vermicomposting), processing by insects and their larvae, composting, and burning. There are three main methods for processing polymer waste: chemical, physico-chemical, and physical. One of the main methods used in construction waste recycling is waste shredding. Processing technology also exists for processing textile waste into secondary raw materials: disinfection, dedusting, sorting, washing, dry cleaning, cutting, oiling, and unwinding. Processing paper and cardboard waste involves the following technologies: the disaggregation of paper and cardboard waste, the purification or release of the mass from impurities, the dissolution of fibers into individual fibers, mass sorting, and refining the waste paper.

Factors in the processing of secondary raw materials that affect the environment arise based on the main types of secondary raw materials for processing and the study of technologies for their processing. According to World Bank forecasts, global waste production will have almost doubled by 2025 as compared with 2000 [42]. Thus, the statistics show that the amount of garbage produced by a country is directly correlated with the level of well-being of the population.

At present, the distribution of global consumer waste production is as follows [43]: 44% of the world's waste is produced in countries that are members of the Organization for Economic Cooperation and Development (OECD); 21% is produced in the Pacific and East Asia; 12% is produced in Latin America and the Caribbean; 6% is produced in Eastern Europe and Central Asia; 5% is produced in South Asia; and 5% is produced in Sub-Saharan Africa. Statistics show that 65% of the total global production of consumer waste occurs in countries with high and above-average income levels. However, in more economically developed countries, technologies for recycling up to 100% of the generated waste are used.

3. Methodology

A general presentation of the methodology is depicted in Figure 1.

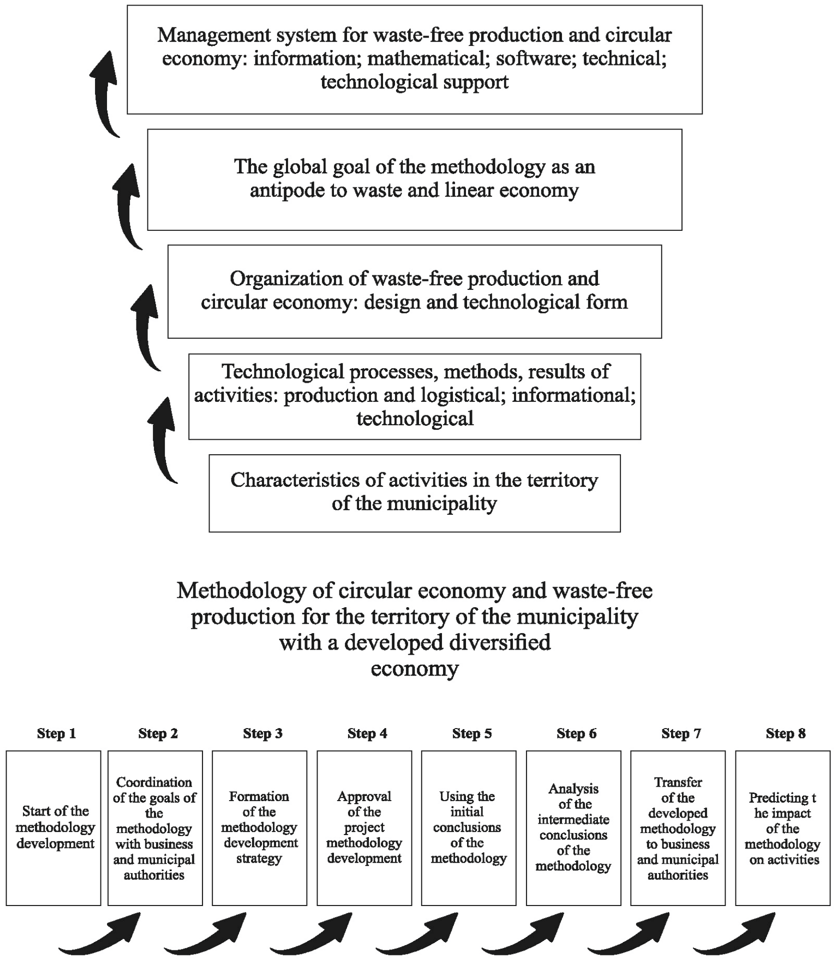


Figure 1. Schematic representation of the elements of the methodology.

The development of a methodology for waste-free production and a circular economy for a specific municipal territory includes the following main tasks:

(a) Development of a goal hierarchy and comprehensive program structure for enabling waste-free production and a circular economy in a municipal area with a developed and diversified economy, and presentation of the hierarchy and structure of goals in the form of a goal tree graph;
(b) Development of a comprehensive program for waste-free production and a circular economy in the municipal area in the form of a mathematical model represented by an alternative graph;
(c) Development of targeted subprograms for the processing of recycled materials for a specific type of recycled product;
(d) Development of a software subsystem for waste-free production and achieving a circular economy: mathematical tools for choosing solutions at the stages of creating and implementing the methodology;
(e) Development of an information support subsystem for the methodology of waste-free production and the circular economy on the territory of the municipality: collection, storage, searching, and processing of data;

(f) Development of a subsystem for providing technologies of waste-free production and the circular economy: collection and development of technologies and knowledge formed on the basis of Industry 4.0 technologies in order to develop a circular economy in enterprises in the municipality;
(g) Development of an information and computing network for the interactions of enterprises located within the territory of the municipality;
(h) Classification of industrial and domestic waste in the municipal area with a developed and diversified economy.

Mathematical tools were used to solve the formulated problems, including graph theory tools of deterministic graphs, alternative network models, cyclic networks, decision trees, and procedures for the synthesis and analysis of programs of an alternative structure (i.e., the decomposition problem of programs of an alternative structure). The basic concept is represented by an alternative network, comprising a directed acyclic network G (J, A) with a set of $J = M \cup D$ and $M \cap D = \varnothing$, where M is the set of program events without alternatives, and D is the vertex set of decisions and program events with alternatives. An alternative structure program has various types according to different durations, costs, and goal achievement probabilities.

Agent-based modeling was carried out in the AnyLogic environment to determine the duration and costs of performing work under uncertainty. Here, the basic concept was simulation modeling, comprising a research method in which the system under study was replaced by a model in order to obtain information about the duration and costs of work.

The analytic hierarchy process involves the selection of a variant for the implementation of a targeted program of a complex structure under the conditions of a certainty of information; the choice of a variant for the implementation of a targeted program of a complex structure under conditions of incomplete information. The basic concept comprises a quantitative assessment of alternative solutions. The quantitative evaluation of alternative solution selection of the five most effective options proceeds according to four criteria. When the alternative structure program is simulated and costs are assessed, it is possible to find options, the number of which depends on the number of alternatives in each operation. The decision-maker selects one of the options as defined by the set of effective options of the alternative structure program.

4. Results

4.1. Comprehensive Targeted Program for Organizing Zero-Waste Production and Solving the Problem of Industrial and Household Waste in a Territory

4.1.1. Integrated Targeted Program: A Set of Inter-Related Subprograms

An integrated targeted program (Figure 2) comprises one of the elements of the zero-waste and circular economy methodology for solving industrial and domestic waste problems in a specific territory.

The composition and hierarchy of the goals of the program were formed on the basis of the development of a tree of goals [44]. Each level has its own structure of goals, which are subgoals relative to the global goal of the program, corresponding to the topmost level. The global goal of the program is as follows: "Create an environmentally oriented system of approaches to the design, production, and processing of goods aimed at preserving the useful qualities of the materials by closing the life cycles of goods. The industrial symbiosis network structure is used to link industrial enterprises, organizations, institutions, and the residents of a particular territory, assuming a paradigm shift in the creation and use of goods in a particular territory based on applying robotics, artificial intelligence, the Internet of Things, 3D printing, cloud computing, Big Data and 5G technology".

An integrated targeted program comprises various targeted zero-waste and circular economy subprograms for a specific type of recycled raw materials (polymer raw materials, secondary wood materials, secondary food raw materials, and others). The structure and hierarchy of the goals of the program were built in the form of a goal graph tree.

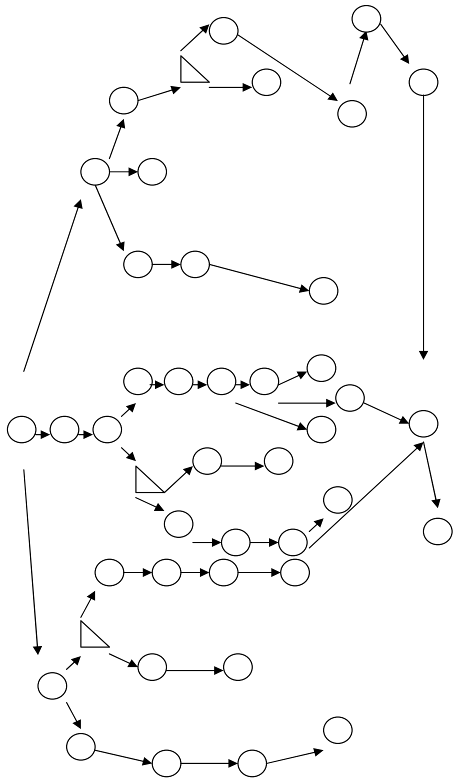


Figure 2. Diagram of an integrated zero-waste and circular economy program consisting of subprograms applied in a specific territory.

The comprehensive targeted program for organizing zero-waste production and solving the problem of industrial and household waste for a specific territory consists of program activities having alternatives and those lacking alternatives. A program event without alternatives can be performed in only one way, while a program event with alternatives can be performed in various ways. In Figure 2, a program event without alternatives is indicated with a circle, while a program event with alternatives is indicated by a triangle.

The program includes program activities for the design and manufacture of products, including the entire life cycle of the product and all interested parties with the requirements for products in a circular economy. Product design and production technology are based on four principles: (a) quickly and conveniently disassembling the product into elements and modules; (b) using materials that can be reused, recycled, or recovered; (c) the composition of the product should not contain hazardous substances that prevent reuse and processing; (d) the manufacturer seeks to extend the life of the product. The program includes cooperation and synergy between companies operating in the area under consideration. The experience of various participants in different industries and other geographic regions is transferred into a comprehensive targeted program.

The involvement of the civil community of the territory is encouraged. This implies the use of a wide range of creative abilities, knowledge, and experience by the type of subcontract work applied voluntarily as part of a comprehensive targeted program.

Consumer behavior is considered to be one of the most important parts in the formation of a comprehensive targeted program for the transition to a circular economy. The product-as-a-service model is one of the most effective tools for moving society toward a resource-efficient, circular economy: product-oriented service; service-oriented architecture; and result-oriented service. The program creates a platform for sharing the same product by several consumers.

The program involves scientific research, technical development, production work, logistics, information support, and organizational measures.

Each process is characterized by certain goals, the scope of the work, and the structure. Structurization of the targeted program represents each of these processes in the form of a rule that reflects the relationship of work and the integration of process structures into a single program structure. Complexes for the processing of secondary raw materials characteristic of the territory comprise elements of the program. An example of a complex for processing secondary polymer raw materials is described in Section 4.2.

4.1.2. Typical Structure of the Targeted Subprogram as an Alternative Graph

The model of a targeted subprogram for organizing zero-waste production and solving the problem of industrial and consumption waste in the territory is presented in the form of an alternative graph in Figure A1 (Appendix A).

M = {mj}, set of program activities;

D = {Dj, djk(j)}, set of decision nodes and alternatives belonging to the program activities that possess them.

T = {tj}, set of technological program activities;

S = {sj}, set of marketing program activities;

G = {gj}, set of geopolitical program activities;

P = {pj}, set of personnel program activities;

I = {ij}, set of investment program activities;

R = {rj}, set of resource program activities.

The program is formed through a cyclic procedure [45]. Any difficulties in linking program activities are resolved through an iterative process that ultimately leads to an alternative program structure. After obtaining such a structure, analysis of the program is carried out. Program activities comprise business processes of the circular economy.

Any difficulties in linking program activities are resolved through an iterative process that ultimately leads to an alternative program structure. The program is analyzed after obtaining such a structure.

Program events include seminars and workshops, where companies from different sectors share their experiences and successful solutions. Crowdsourcing procedures are used to solve the problem of domestic waste. The program includes program activities that provide for voluntary cooperation between enterprises, whose purpose is to reduce production costs using by-products and waste from some enterprises as raw materials for the production cycle of other enterprises.

4.2. Targeted Subprogram for Organizing Zero-Waste Production and Solving the Problem of Industrial Waste Types: Example of Modeling the Process of Recycling Secondary Polymer Raw Materials

The processing of secondary polymer raw materials within the comprehensive targeted program is presented in the form of an alternative graph for displaying various options for performing work or achieving local goals along with the global goal of the subprogram. Moreover, the choice of an option to achieve a local goal is carried out not according to a local criterion, but rather from the point of view of the targeted subprogram. Thus, for example, it may be necessary to select between the option to develop and produce a technical complex for the processing of secondary polymer raw materials or the option to purchase an existing complex for the processing of secondary polymer raw materials on the market. As an example of recycling secondary raw materials, a complex for reprocessing plastic waste from the Polystar Company was taken. This complex is designed for the processing of roll film, raffia, and hard plastic. The complex processes waste into granules, which can be used in the future.

The organization of the processing of secondary raw materials was modeled as an alternative graph. The first stage of the process of organizing the processing of secondary raw materials is the presentation of the goals in the form of a tree graph [46]. An enlarged tree graph of the goals of the recycling process of secondary polymeric raw materials is shown in Figure 3.

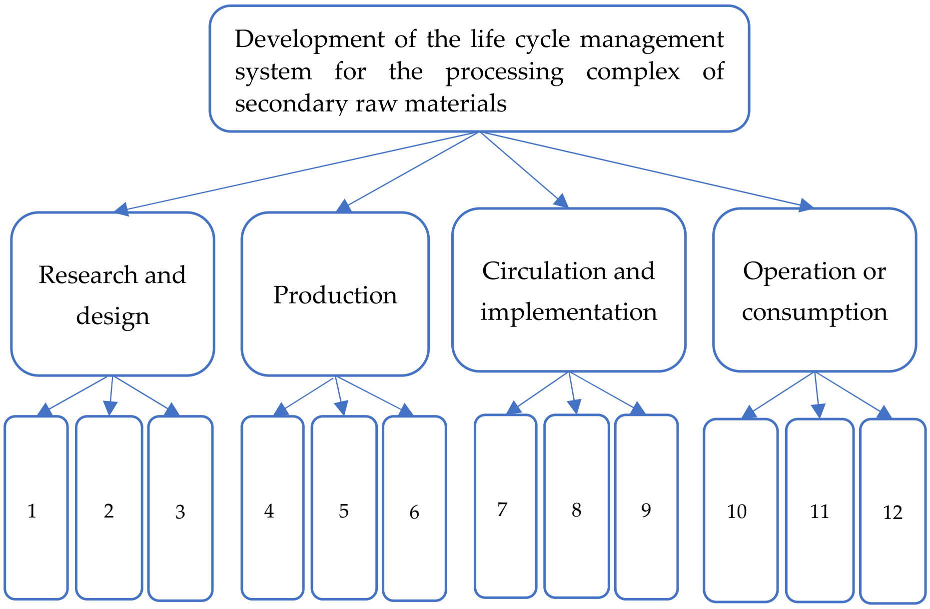


Figure 3. Decomposition of the global goal of the recycling process of secondary polymeric raw materials in the form of a tree graph.

The decomposition of the global goal of the process of organizing the processing of secondary raw materials was carried out using the life cycle stages of the complex. The entire life cycle of the complex for the processing of secondary raw materials is presented in the form of four enlarged stages. These are presented at the first level of decomposition: research and design; production; circulation and implementation; and operation or consumption. The above stages are divided at the next level of decomposition into smaller work-program activities designated from 1 to 12. The alternative column demonstrates the performance of work using various technologies, i.e., there is a variance in achieving local goals. Each option has its own duration, costs and technical result level.

The "Research and Design" stage includes program design: marketing research of existing complexes, the development of the project of the complex, and the creation of a prototype complex.

The "Production" stage includes the purchase of raw materials for the production of the complex, and the control and examination of the complex.

The "Circulation and Implementation" stage includes the implementation of the complex, delivery of the complex to the buyer, and installation of the complex.

The "Operation or Consumption" stage includes the operation of the complex, repair of the complex, and disposal of the complex.

The decomposition of the global goal of creating a complex for the processing of secondary raw materials in the form of a graph tree is necessary for the formation of all the options for performing the work of the model of processing secondary polymer raw materials.

An alternative graph of the processing of secondary polymer raw materials is shown in Figure A2 (Appendix B). In the recycling process model, some concepts are marked with a triangle, for example, D1, D2, and D3. These are works that are carried out in different ways. The circles following the triangle represent work options [44].

The duration of each work was determined by the following condition: during the entire period, labor costs are associated with a certain number of actors required to complete the work. The duration of some projects was defined analogously with work performed during previous periods. In this case, the duration of a work is a deterministic value. The process of performing work has a solid regulatory framework; temporary estimates of work productivity receive relatively definite values corresponding to normal working conditions. In other words, the work's duration can be described with a probability equal to one. However, because there are no objective and reasonable norms for the duration of individual works, their duration had to be determined under conditions of risk or complete uncertainty. This applies, for example, to research and experiments. To determine the duration of the operation, the set of effective options of alternative structure program simulation modeling was used, assuming that the duration of the work is a random variable that can be characterized by a β-distribution law [47]. Simulation modeling was carried out in the AnyLogic environment. The authors chose agent-based simulation, which sets agents with different operational durations for the alternative structure program, including the possibility to build connections between these agents. Agent-based simulation enables each participant of the process to be assigned an agent role marking limitations and characteristic features. The results corresponding to the selected input parameters for agent-based modeling in the AnyLogic environment are shown in Figures 4–8.

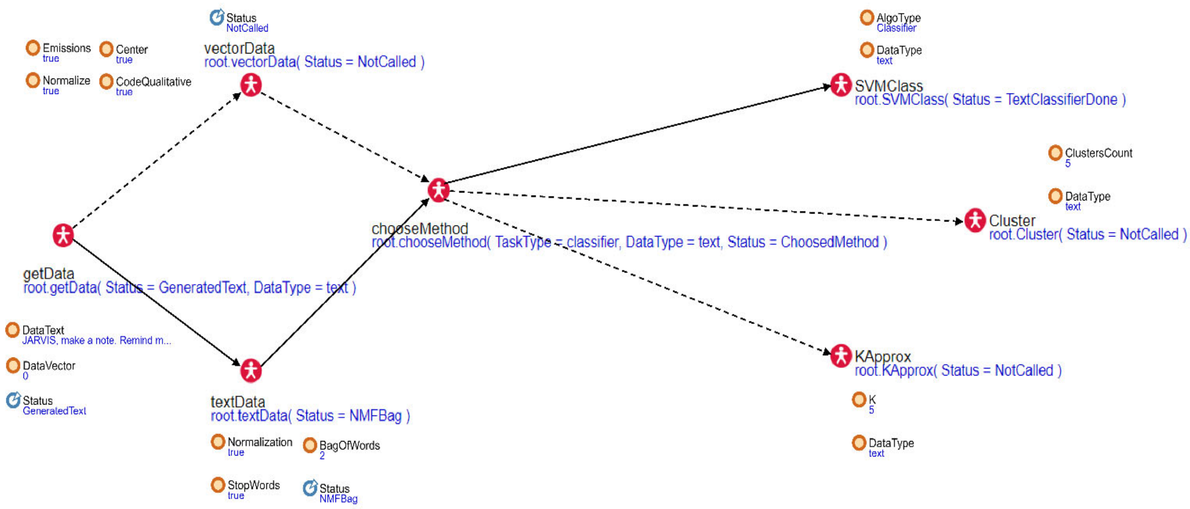


Figure 4. Model run with text data, adopting the classifier machine learning method.

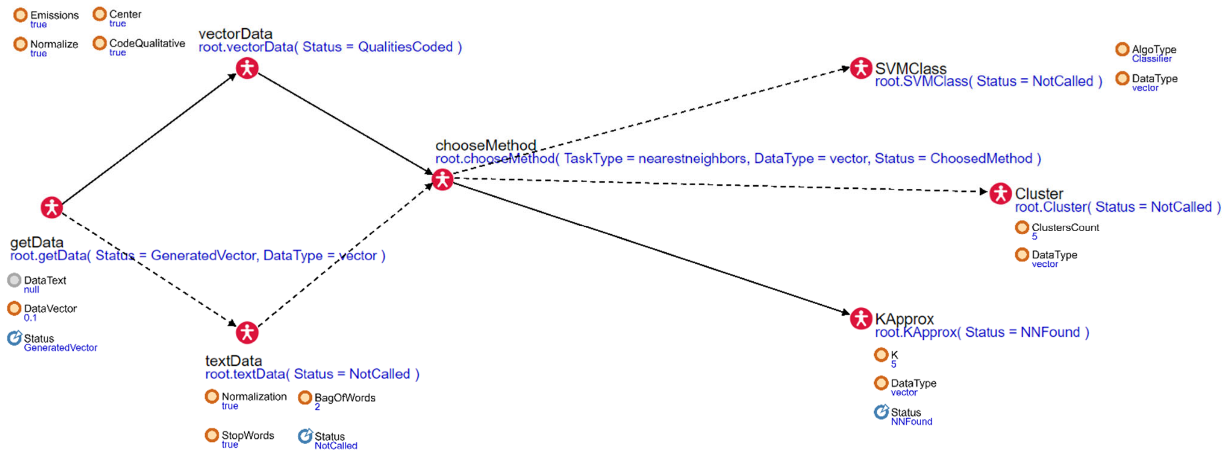
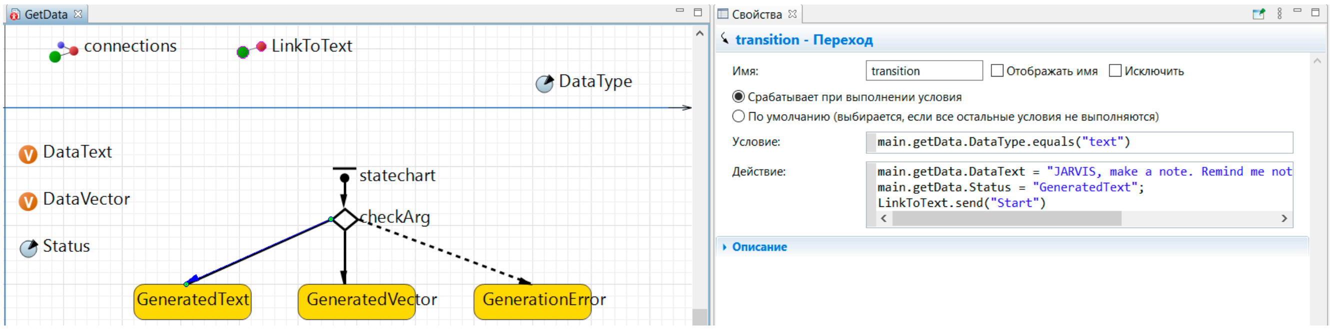


Figure 5. Model run with vector data, adopting the approximate nearest neighbor search machine learning method.

The constructed model with established connections between agents is shown in Figure 4 (agent-based modeling in terms of working with text data) and in Figure 5 (agent-based modeling in terms of working with vector data).

Each agent is represented either by a state diagram, for which the conditions for transition from state to state are specified (see Figure 6), or by an action diagram (see Figure 7).



(a) (b)

Figure 6. The GetData class for generating input data is defined by a state diagram. (**a**) agent state diagram; (**b**) conditions for the transition of an agent from state to state in non-English terms in the JAVA language.

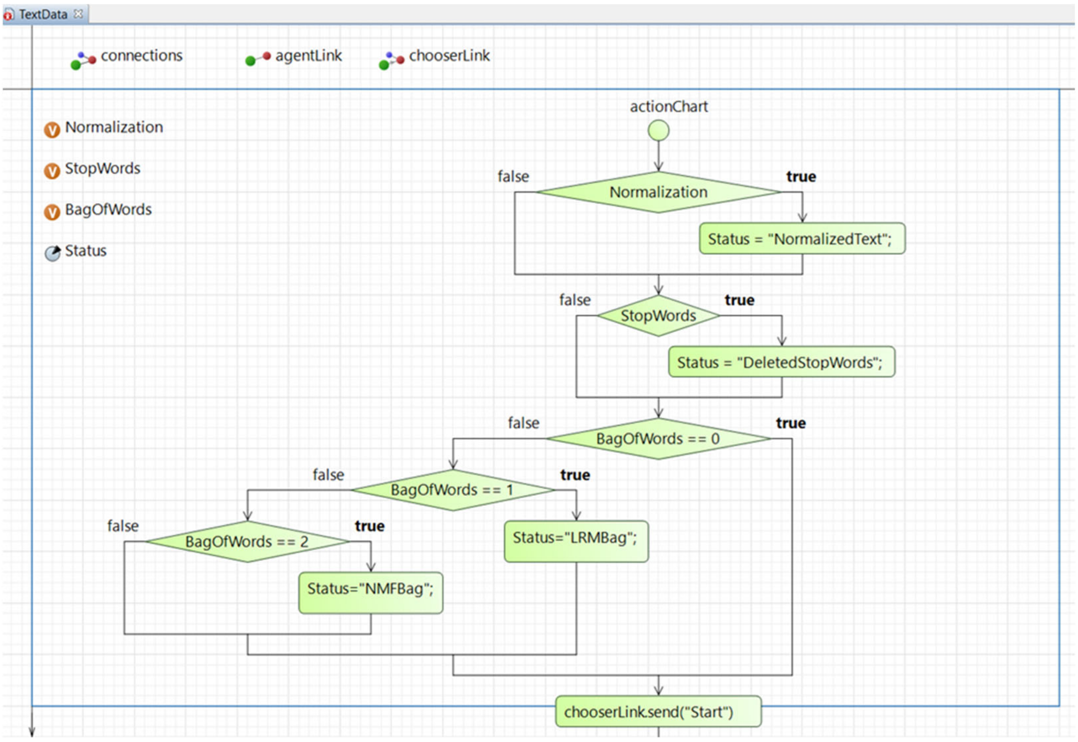


Figure 7. The TextData class for preprocessing text data is defined by the action diagram.

Each agent has its own variables and parameters that can be set by the user depending on the task, and variables that take on their values depending on the actions of the associated agent. Each agent has a Status parameter that displays the current state of the agent.

The results of modeling agents with different duration of work in the conditions of processing text data, and in the conditions of processing vector data, are shown in Figure 8.

The alternative graph of the recycling process of secondary polymer raw materials is set out in Figure A2. Options for the implementation of the project are shown in Figure 9. The processing of secondary polymer raw materials was modeled by the alternative graph with two technical levels. The effective set of options for processing secondary polymer raw materials of the first scientific and technical level is highlighted in blue; the second, higher scientific and technical level, is highlighted in yellow.

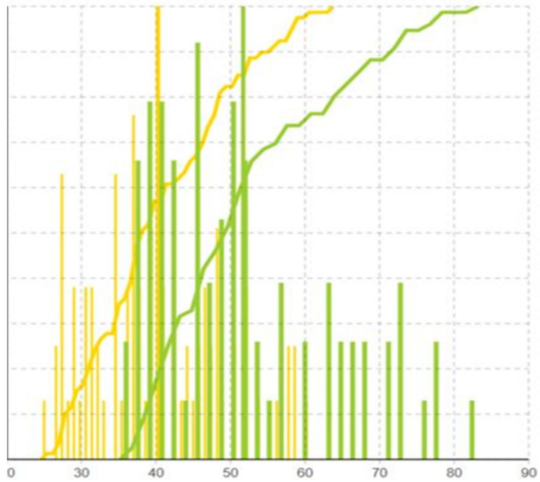


Figure 8. The result of modeling the duration of work: in the conditions of processing text data (yellow); under vector data processing conditions (green).

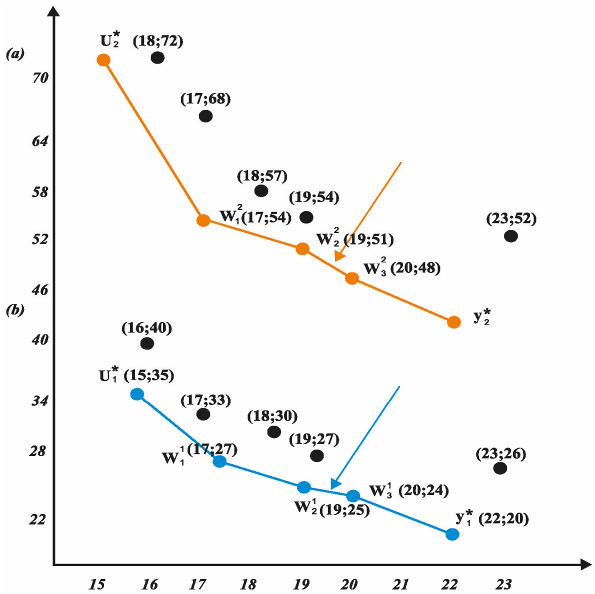


Figure 9. Graph of cost dependence on the duration and scientific and technical level: efficient multiple recycling process options with two technological levels: (**a**) second higher scientific and technical level, (**b**) first scientific and technical level.

An alternative structure program has several options due to varying durations and costs, as well as different scientific and technical levels. The number of options depends on the number of alternatives of each operation, and can be large. All options are divided into two sets. Options with a closed interval [T*, T_K*] and conditions:

$$T_1 < T_2 < \cdots\ldots < T_i < \cdots\ldots < T_K,$$

$$K_1 > K_2 > \cdots\ldots > K_i > \cdots\ldots > K_T$$

are called the set of effective options, but all others are a set of ineffective options.

Figure 9 shows the set of effective options, including five options of the second higher scientific and technical level, which is highlighted in yellow, while the set of effective options with seven options of the first scientific and technical level is highlighted in blue. The set of ineffective options is not presented in the figure since, for each set of ineffective options, there is a better set of effective options. It is necessary to choose one of the options among the set of effective options, which includes the five options of the second higher scientific and technical level.

Choosing one option from several was carried out using the analytic hierarchy process [48]. The analytic hierarchy process does not prescribe any "correct" decision to the decision-maker (DM), but enables them to interactively find the variant (alternative) that best fits their understanding of the problem and the requirements for solving it.

The analytic hierarchy process includes a goal, criteria, and alternatives (Figure 10).

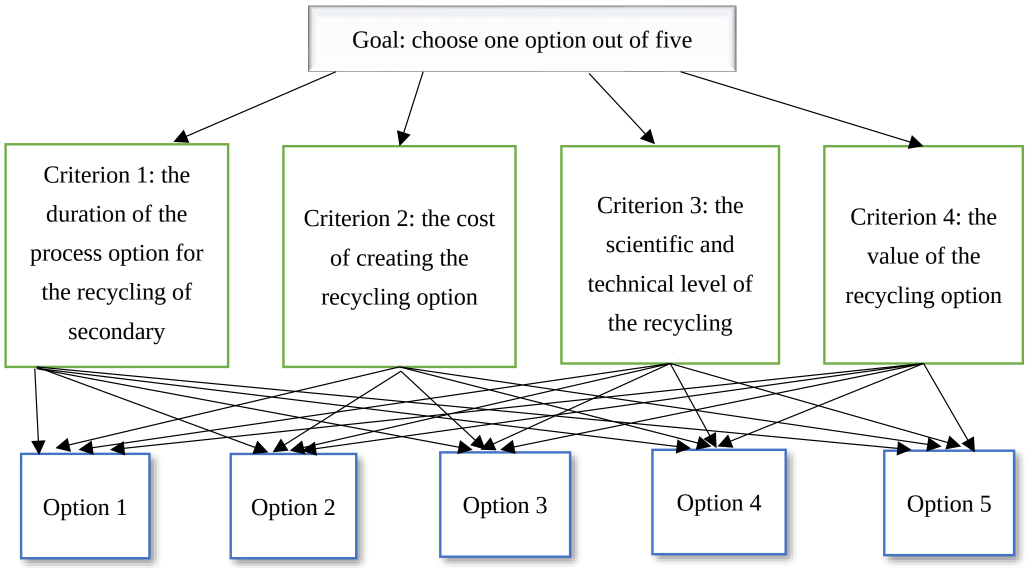


Figure 10. Analytic hierarchy process sequence.

In our case, the goal within the analytic hierarchy process is formulated as "the choice of one option for the processing of secondary polymer raw materials from several options, each of which has different parameters".

The following criteria for evaluating options for the processing of secondary polymeric raw materials are considered: the duration of the chosen process for recycling secondary polymeric raw materials; the cost of establishing the recycling option; the scientific and technical level required for the recycling option; and the value of the recycling option.

The scientific and technical level of the processing of secondary polymeric raw materials variant is estimated by the performance of the complex for processing secondary polymeric raw materials.

The alternatives comprise five specific options, which are shown in Figure 9 in a two-dimensional space: "dependence of costs on duration and scientific and technical level".

The problem is to choose one of the five options against four criteria. A pairwise comparison of criteria against the main goal of the task is applied. The analytic hierarchy process includes a priority design procedure, which is calculated based on subjective experts' opinions. The main concept of this method consists of the pairwise comparison of criteria. All four criteria for choosing one of the options are estimated using the pairwise comparison matrix. The best option is considered to be the one demonstrating the maximum priority value.

4.3. Mathematical, Software, and Informational Tools of the Methodology Simulation of an Integrated Zero-Waste and Circular Economy in a Specific Territory

The mathematical, software, and informational tools of the methodological simulation of an integrated zero-waste and circular economy in a specific territory include a system of data collection, database, mathematical models, and software tools.

The data collection system comprises a computer system, which collects data against physical parameter values at given points of the study object, including initial processing, collecting information, and data transmission.

The database of mathematical, software, and informational tools is based on (a) a waste inventory and (b) circular economy models and technologies.

A waste inventory comprises an administrative document of the municipal district, which contains waste utilization, recycling, and landfill disposal data, taking the form of a classified and catalogued register of all kinds of industrial and domestic waste.

The waste inventory is used to archive the data of waste origins, amounts, contents, and properties for each economic unit; the regulation of raw material; industrial and domestic waste landfill disposal; means for its transportation and utilization; and waste recycling, sterilization, and utilization algorithms in a municipal district.

Circular economy models and technologies generated in a database which can be used in the territory of a municipal district are also potentially useful for reducing greenhouse gas emissions, optimizing the use of raw materials, and increasing agricultural efficiency, as well as generally decreasing the negative external impacts of the linear economy. This may take the form of renewable energy, which, in the long term, pollutes the environment less than fossil fuel, as well as circular suppliers, resource recovery, product life extension, sharing platforms, product as a service, remanufacturing, ecodesign, downcycling, disruptive innovation, and smart containers for separate waste collection.

The database represents an informational basis for creating and improving targeted subprograms of zero-waste production and industrial waste by the specific type of waste, as well as a mathematical model represented by an alternative graph comprising an essential basis for shifting to a closed economy.

5. Discussion

The present study confirms the necessity of reorganizing the local economy by creating integrated systems of zero-waste production and industrial and domestic waste recycling in a specific territory. On the one hand, integrated systems of zero-waste production and industrial and domestic waste recycling improve ecology and quality of life in a specific territory. On the other hand, integrated systems of zero-waste production and industrial and domestic waste recycling stimulate the growth of the local economy with simultaneous investments and the generation of employment.

The goal of this study was to simulate a new model of an integrated system of zero-waste production and the circular economy in a specific municipal district with a developed, diversified economy. The model was simulated on the basis of different theories and scientific approaches: graph theory, goal management, and decision theory. The mathematical model of integrated zero-waste production and industrial and domestic waste in a specific territory presented as an alternative graph enables the creation of goal achievement options, as well as defining the investment amounts for each option. The mathematical model of integrated zero-waste production and subprograms by the type of waste are digital twins of the transition from a linear economy to a circular economy. Digital twins are used in simulating, forecasting, and optimizing the process of shifting from a linear to a circular economy in a specific territory.

The attractiveness of the transition from a linear economy to a circular economy in a specific territory, including the active promotion of ecological sustainability and inclusive economic growth, can be used to attract new followers of this idea. Available technologies and scientific knowledge comprise valuable assets; uniting such factors into a logical strategic perspective can support the sustainable development of an area by creating high-value-added jobs while as protecting the environment, improving air quality, and enhancing the quality of life in general.

The practical goal of an integrated zero-waste and circular economy model is to provide IT and mathematical support by creating and updating the technology database of zero-waste production and the circular economy.

The research has demonstrated the effectiveness of an integrated zero-waste and circular economy model applied in a specific municipal territory. At the same time, the results reveal that current plans and management approaches may be less effective for achieving the Sustainable Development Goals.

The application of an integrated zero-waste and circular economy methodology applied in a specific territory comprising a municipal district with a developed and diversified economy represents a novel approach in the academic management literature. According to government and business officials, it is necessary to shift towards a zero-waste and circular economy by means of integrated alternative projects. In order to effectively coordinate the shift from a linear economy to a circular economy, it will be necessary to consider that this transition is a complicated, multilevel, and long-term process.

6. Conclusions

The 2030 Sustainable Development Goals adopted by the UN in 2015 imply a transformation of the linear economy model. The transition to a circular economy will require modernization and innovation in production. Waste recycling and reuse are important elements of the circular economy. Many specific territories face serious socio-economic problems, including those associated with the transition to a circular economy. The technology of the linear economy is well developed and has the largest percentage of jobs in any field. The cooperation of local authorities, the local population, enterprises, and organizations are necessary elements; new initiatives may be required to ensure the effective orientation of the territorial economy towards the transition from a linear to a circular local economy. Economic barriers and the low investment attractiveness of circular economy technologies represent barriers to obtaining sources of funding for the active use of circular business models and the reorganization of existing linear processes. There is also a need to train employees of companies, organizations, and local authorities in a wide range of disciplines related to the use of circular business models in various industries in order to ensure the environmental, economic and social benefits that can be obtained from their application.

The preliminary conclusions of the results demonstrate the importance of improving cooperation between local government and business in order to effectively put zero-waste and circular economy concepts into practice.

The social economic development of the territory represents a promising avenue for cooperation between local government, businesses, and residents. Such cooperation is presented by such business models as person-to-person (P2P), business-to-business (B2B), or business-to-people (B2P) interactions. The mutual interest of government and business can become a basis of their partner relations in a zero-waste and circular economy.

The primary motivation for putting the concept of a zero-waste and circular economy into practice in a specific territory consists of the need to comply with waste inventory laws, according to which companies and business owners must perform waste inventory reporting. The waste inventory of production and consumption represents an informational basis for regulating the waste problem, providing a motivation for businesses to pay attention to this problem.

An integrated zero-waste and circular economy program in a municipal district comprises a mathematical model represented by an alternative graph, and is an essential basis for the shift to a closed economy by putting the concept of zero-waste and the circular economy into practice. Empirical analysis of the methodology carried out in the municipal district has demonstrated the positive feedback of companies and government officials to the targeted subprograms of zero-waste production and solving the industrial waste problem according to specific types of waste, as shown as in the mathematical model and represented by an alternative graph. However, not all transformations should be regulated by programs, since a program has a set of options, each with its own duration, costs, effectiveness, and technical level. A decision-maker can choose an option of zero-waste and the circular economy by selecting one, two, three, or four parameters.

Author Contributions: Conceptualization, N.D. and D.S.; methodology, N.D. and D.S.; software, K.N.K. and K.S.; formal analysis, N.D., D.S., A.G. and K.N.K.; investigation, N.D., D.S., A.G., K.N.K. and K.S.; resources, N.D. and A.G.; data curation, N.D., D.S. and A.G.; writing—original, N.D., D.S., A.G., K.N.K. and K.S.; writing—review and editing, N.D. and D.S.; visualization, A.G., K.N.K. and K.S.; supervision, N.D.; project administration, D.S. and A.G. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

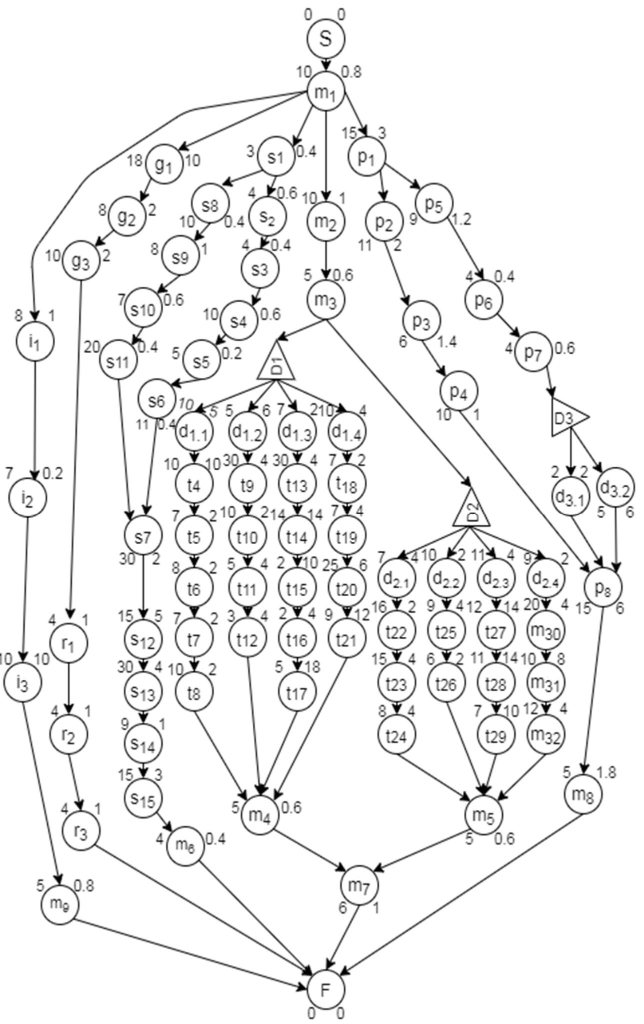

Figure A1. An alternative graph of a typical targeted subprogram for organizing zero-waste production and solving the problem of industrial and household waste in the territory.

Appendix B

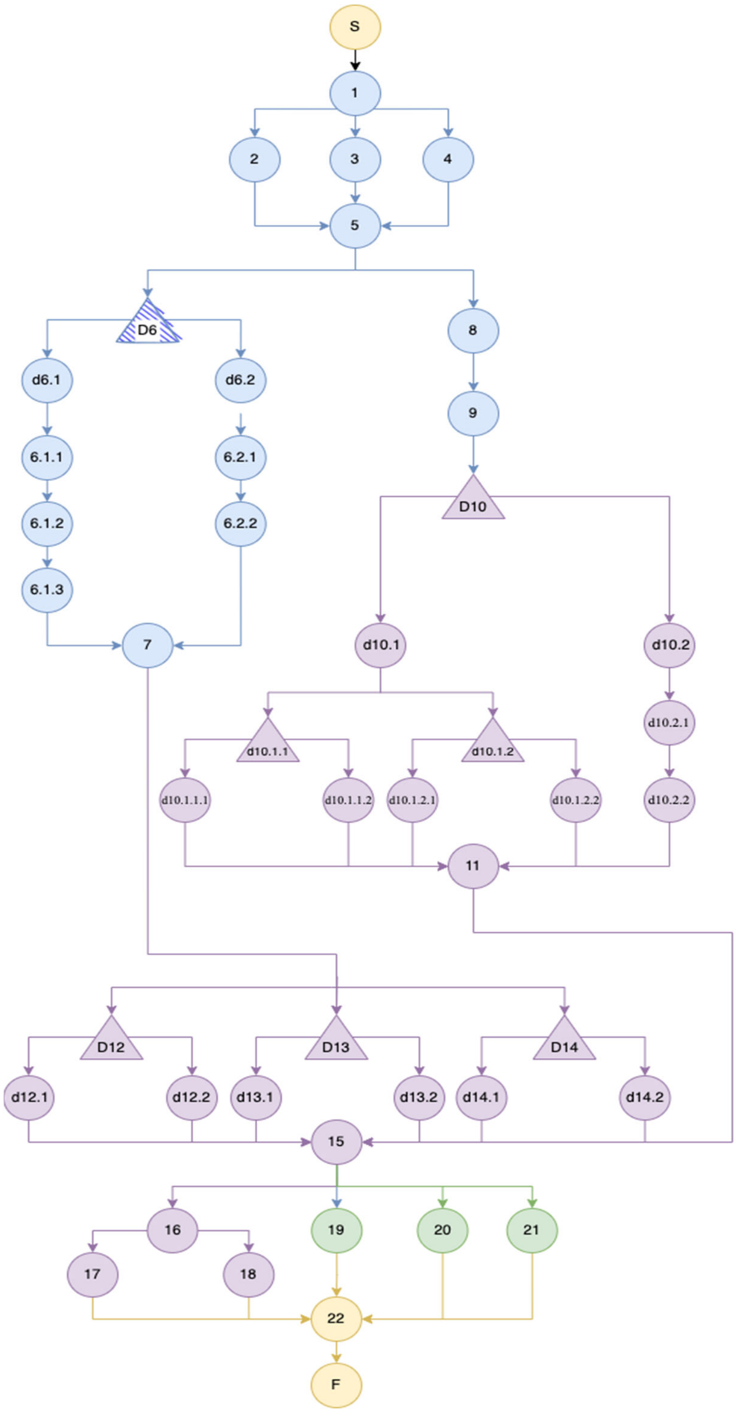

Figure A2. The alternative graph of the recycling process of secondary polymer raw materials.

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