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Development of modules for an integrated GIS system for predicting impact zones of separating rocket stages

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Abstract

The article presents a comprehensive approach to the development of modules for a multifunctional cartographic resource for predicting impact zones of separating parts of launch vehicles. The proposed solution is based on the integration of mathematical models, including ballistic, stochastic, and adaptive algorithms, with geographic information systems (GIS), which allows for highly accurate spatial risk analysis. The study developed the architecture of a software package that includes modules for collecting, processing, and visualizing data, as well as algorithms for generating thematic and geocognitive maps. Particular attention is paid to the possibility of further integration of the system with external information platforms meteorological services, digital twins, warning, and monitoring systems. The modeling conducted on various scenarios showed that the use of artificial intelligence and automated map generation can reduce the average forecast error to 60 meters and significantly increase the reliability of risk zone assessment. The results of the work can be used to improve the safety of space launches, support decision-making in emergency situations, as well as in territorial planning and environmental monitoring.

Keywords: Automation, Axiomatics, Digital Map, GIS, Mathematical modeling.

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1. Introduction

In the context of intensive development of aerospace activities and increasing frequency of launch vehicles, the need for accurate, adaptive, and scalable systems for assessing risks associated with the fall of separating elements is growing. The task of promptly forecasting areas of possible damage on the earth's surface and integrating these forecasts into decision support systems operating in real time is particularly acute. Traditional methods of calculating trajectories, based primarily on classical ballistics, are increasingly supplemented or replaced by hybrid approaches that include elements of machine learning, adaptive modeling, and geoinformation analysis.

One of the key areas in solving this problem is the development of multifunctional cartographic resources capable of not only processing input data of various natures from aerodynamic parameters to meteorological and demographic factors but also providing visualization and analysis of spatial risks on interactive digital platforms. Geographic Information Systems (GIS), which have a high degree of scalability and open architecture, are becoming the basis for creating such solutions, integrating the functionality of spatial analysis, cartographic visualization, and modular interaction with external information systems.

This study aims to develop the architecture and basic modules of a multifunctional GIS resource for predicting impact zones of separating parts of rockets. The proposed model is based on a combination of ballistic, stochastic, and adaptive approaches with cartographic modeling, automatic generation of thematic maps, and the possibility of further integration with external systems, including monitoring platforms, digital twins of territories, meteorological services, and information and analytical systems of civil protection services.

The article Juho and Han [1] presents an overview of modern separation and discharge systems in aerospace systems with a detailed comparative analysis of the efficiency of various designs. The authors pay special attention to mathematical models of the behavior of parts after separation and adaptive methods of safety control, including the use of GIS for assessing risk areas. The article emphasizes the role of new materials, electromechanics, and control algorithms to minimize the risks of emergency situations. Among the cases considered is the integration of monitoring systems with spatial data and weather conditions for predictive assessment. Examples of successful implementation and analysis of emergency scenarios, recommendations for the development of the industry are given. The directions of development of adaptive algorithms and digital twins in ensuring safety are summarized. Article Xu et al. [2] is devoted to a detailed mathematical analysis of the motion of stages after separation, taking into account aerodynamics and the influence of meteorological conditions. The authors use a system of differential equations that take into account variable mass, environmental resistance, and crosswind, which allows reproducing the real movement of objects. An important part of the study is the calibration of models using archived launch data and calculating the probability of parts leaving the safe zone. The methods for constructing maps of impact areas with integration into domestic GIS are considered. The results are compared with experimental data, demonstrating high accuracy and applicability of the methodology for operational planning. A comprehensive warning system with automatic generation of maps and recommendations for security services is proposed. The article Gan et al. [3] develops a semi-quantitative algorithm for assessing the risks of damage to objects on the ground by falling rocket parts. To improve the accuracy of calculations, the integration of ballistic models with GIS is used, which allows dynamically updating hazard maps based on real weather and navigation data. A method of spatio-temporal analysis is described: not only the location, but also the probability and time interval of the appearance of a dangerous object is predicted. The work includes examples of implementation at Chinese spaceports and the results of comparison with traditional models. The importance of adaptive approaches that allow promptly adjusting calculations when the trajectory or wind changes is emphasized. Recommendations for organizing warnings and evacuation measures for the population are introduced. The paper Acquatella and Reiner [4] proposes a comprehensive method for assessing the risk to population and infrastructure from rocket debris by integrating ballistic modeling with GIS-based spatial analysis. The authors apply advanced GIS techniques to map likely impact zones and develop scenario-based approaches to minimize damage. The study includes an algorithm for dynamically adjusting hazard zone boundaries based on updated trajectories and weather data. The effectiveness of the method is demonstrated using real launch examples, showing how automatic warnings can be generated for the public and authorities. Integration with land-use databases allows taking into account population density and critical infrastructure when predicting impacts. Validation results and comparative effectiveness with standard protocols are presented. This paper is of great importance for civil protection services and safety management at spaceports. The paper Collins and Kirby [5] is devoted to modeling complex dynamic processes during stage separation, including taking into account multibody interactions and oscillations. An original adaptive algorithm for calculating transient processes is proposed, which minimizes computational errors at critical moments (separation, aerodynamic stall). The results are integrated into a GIS, allowing to generate maps of possible trajectories and fall zones. Comparative tests of various models, as well as examples of practical application at European and Russian launch complexes, are provided. Aspects of interaction with observation systems and big data processing are considered separately. The work is relevant for mission control centers, launch operators, and dynamics specialists. The prospect of integrating the model with meteorological observation data and adaptive sensor networks is also discussed. The authors use Monte Carlo methods to model uncertainties in the process of stage separation and calculate their possible fall zones. The model takes into account a wide range of initial conditions from navigation errors to wind variability at different altitudes. The analysis results are visualized in a GIS and allow identifying areas of greatest risk for planning ground activities. A comparison of the effectiveness of traditional and adaptive approaches to predicting debris distribution is carried out. The application of the model for analyzing emergency situations and generating reports for aviation and rescue services is discussed in detail. The article presents examples with different types of rockets (single- and multi-stage systems). A conclusion is made about the need to integrate Monte Carlo calculations with modern geoinformation platforms for decision-making [6]. The paper Luchinsky and Hafiychuk [7] describes a stochastic approach to analyzing the trajectories of rocket parts under the influence of random lateral loads. The Ornstein-Uhlenbeck process is used to simulate fluctuations in direction and speed that affect the final distribution of the fall. The authors study in detail the influence of unpredictable aerodynamic effects in the atmosphere on flight safety. The proposed model is easily integrated into GIS and can be used to generate a probability distribution of the fall of individual elements at different stages of the mission. Practical calculations are given for several types of launch vehicles with different separation configurations. Conclusions are made about the importance of taking into account rare but significant trajectory deviations for early warning systems. Recommendations include strengthening control over the real wind profile near the launch site. The article Wang et al. [8] is devoted to the issues of diagnostics and prediction of failures during separation of launch vehicle stages based on complex modeling. The methods of early detection of anomalies and development of prognostic indicators at all stages of flight, including in real time, are considered. The models are integrated with sensor and GIS systems to automatically display potentially hazardous situations and assess the consequences. Particular attention is paid to the validation of approaches on historical data and implementation in operator action protocols. The work illustrates examples of critical incidents and describes how modern digital methods can reduce the number of emergency scenarios. The article is relevant for mission control centers and risk analysis teams. Directions for the development of artificial intelligence systems to increase the autonomy of analysis are proposed. The paper Wang et al. [8] proposes a comprehensive method for assessing the risk to the population and infrastructure based on the integration of ballistic models with GIS. The authors use spatial analysis to map probable impact zones and build damage minimization scenarios. An algorithm for dynamically adjusting the boundaries of hazardous areas is presented based on incoming data on the trajectory and weather conditions. The possibility of automatic generation of warnings for the population and responsible services is discussed. The article Zhou et al. [9] considers in detail the interaction with land use databases, which allow taking into account the density of development and the placement of critical facilities. The criteria for the effectiveness of models and methods for their validation are proposed using real launches as an example. The article Wang and Zhou [10] creates a comprehensive mathematical model of the dynamics of multiple separation of stages, taking into account internal interaction, aerodynamics, and environmental parameters. The model provides for adaptation to changing external conditions, which increases the accuracy of calculations of the final fall point for each element. Simulation algorithms based on real flight and weather data are given, as well as methods for visualizing the results using GIS. The work includes examples of scenarios with emergency modes and consideration of methods for minimizing damage when parts go beyond the calculated zones. A separate description is given of the procedure for calibrating the model based on the results of tracking data analysis. An overview of the method application for new reusable stages is given. Recommendations concern the integration of models into support systems for launch complex operators. The article Katona and Kis [11] is devoted to the development and validation of a model for analyzing the trajectory and forecasting the impact areas of the boosters. Particular attention is paid to taking into account the actual wind profile and interaction with flows at different altitudes. Adaptive filters are used to correct the trajectory in real time based on radar and satellite data. The resulting forecasts are automatically integrated into digital GIS maps to generate reports and alert decision makers. Comparative tests of efficiency with existing protocols are provided. The possibility of using the algorithm to optimize evacuation routes and plan ground operations is noted. The authors emphasize the importance of feedback from surveillance systems to improve accuracy. The article Ishikawa and Suzuki [12] considers the practical issues of integrating ballistic calculations with Russian GIS platforms for constructing stages and debris fall zones. An architectural approach to the development of geospatial analysis modules and their integration with meteorological and population data is described. Modeling is carried out taking into account the specifics of the terrain, infrastructure, and possible emergency department scenarios. Examples of visualization in the form of interactive maps, as well as automated report generation for the Ministry of Emergency Situations and security services are given. Issues of data exchange between various departments and standardization of the data format are discussed. The work is illustrated with real cases from regions of Kazakhstan and Russia. A conclusion is made about the feasibility of further automation of processes and integration into unified monitoring platforms. The article Zhang and Liu [13] considers modern methods of adaptive control and trajectory optimization for multistage rockets in order to minimize the risks of a fall and maximize the accuracy of payload delivery. Hybrid approaches are used that combine classical modeling with elements of machine learning to predict possible deviations. The models are tested on simulators and verified using launch data. The results are integrated into a GIS to build scenarios for the development of events and automatic adjustment of fall routes. Methods are proposed for automatically updating model parameters depending on weather conditions and terrain characteristics. The article contains a generalized analysis of the prospects for the development of adaptive technologies in the aerospace industry. The possibilities of integration with national monitoring and decision support systems are described. The article Wang and Zhou [10] is devoted to the experience of creating automated GIS complexes for predicting stages' fall areas using domestic cosmodromes as an example. The authors develop an architecture that combines ballistic modules, spatial data processing, and visualization in a single interface. Much attention is paid to the issues of terrain detailing and land use to improve the accuracy of the model. Cases of integration with national meteorological systems and scenarios for mass launches are provided. Information exchange with departments and compliance with regulatory safety requirements are discussed. The possibilities of promptly updating maps and reports in real time are illustrated. The paper Wang and Xu [14] presents an approach to assessing the risks to the population and infrastructure in the event of falling rocket debris using statistical analysis and GIS. The Monte Carlo method is used to simulate possible trajectories, taking into account a large number of random factors (wind, errors in the separation system, etc.). The final results are integrated into digital maps, allowing for the most dangerous areas to be quickly identified. Recommendations for operators and emergency services on the use of information for evacuation planning are provided. Examples of the method implementation in different countries (Japan, USA, EU) are considered. The authors analyze possible ways to improve the accuracy of forecasts and automate calculations. The article Negri et al. [15] presents an overview of the concept of a digital twin (Digital Twin) and its role in cyber-physical production systems (CPS). The authors highlight the main areas of application of digital twins: modeling and simulation, real-time monitoring, optimization, and decision support at all stages of the product life cycle. The technological requirements and architectures for the successful implementation of a digital twin in industry are described. Special attention is paid to the issues of data integration from the physical and virtual levels, as well as the prospects for the implementation of Digital Twin for increasing the efficiency, flexibility, and reliability of production. The book Graser [16] describes a practical guide to working with QGIS, one of the most popular open GIS platforms. The author examines the basic and advanced functions of QGIS step by step: from data import and visualization to spatial analysis, geoprocessing, and creation of interactive maps. The book includes examples of real-world problems, tips on customizing the interface, working with plugins, and integrating QGIS with other GIS tools. It is recommended for both beginners and experienced users for independent study of modern approaches to working with geographic information systems. The article Byers et al. [17] calculates the risk to the population in the Global South due to uncontrolled entry of upper stages and their debris. Legislative regulation is proposed to prevent failures in controlled entry. The article Lee et al. [18] presents an overview of 1D / 3D models (MOCAT, SOLEM, etc.), with an in-depth analysis of debris propagation algorithms and the development of Korean engineering space. The paper Rao and Rondina [19] presents a physical-economic model of LEO debris, indicating Kessler syndrome by 2035–2048 without active measures. The paper Slíz-Balogh et al. [20] presents a mathematical model of spherical debris trajectories of different sizes, taking into account air resistance, and many fall parameters are determined analytically. The paper Xu et al. [21] presents a mathematical model of a two-level TSP problem for debris removal mission planning: DNN and RL are used to estimate Δv and optimize the trajectory.

The aim of the work is to develop an integrated approach to mathematical modeling and forecasting of impact zones of separating parts of launch vehicles using geoinformation systems and modern analytical methods to improve the accuracy of risk assessment and ensure safety during space launches.

2. Research Methodology

In the modern conditions of ensuring the safety of space launches and minimizing risks to the population, a special role is played by the construction of reliable mathematical models for predicting the areas of impact of separating parts of launch vehicles. The basis of such models is the integration of ballistic, probabilistic, and geoinformation methods, taking into account physical, meteorological, and demographic factors. This section presents the theoretical and algorithmic foundation of the proposed model, which includes:

- Formalization of the initial spatial and thematic data;
- Use of professional knowledge and modern methods of processing GIS information;
- Mathematical description of the motion of separating parts, taking into account aerodynamics and wind loads;
- Elements of probabilistic modeling and automation of thematic map creation.

This approach allows not only the calculation of expected impact points but also the implementation of an adaptive decision support system for various launch scenarios.

Let's consider the mathematical model that underlies the construction of a cartographic resource. The main components of the model are the initial data for construction:

- The geographic basis of the map for a given territory *T*, which is represented as a set of geographic objects D_g, specified as a data array;
- Thematic basis of the map for a given territory *T*, which is presented in the form of a set of geospatial objects D_t, specified as a data array;
- Professional knowledge in the field of cartography Z_k;
- Professional knowledge in a given subject area Z_t;

These arrays D_g and D_t are subjected to the process of joint processing F_d(1), based on the professional knowledge of Z_k and Z_t. As a result, an array of geospatial information is formed in the form of a geoinformation thematic model MT for a given territory *T*. This model describes the spatial objects of the territory and includes data on their spatial position and characteristics according to the established subject area.

$$F_d :< \mathrm{Z}_k, D_g, Z_t, D_t > \Rightarrow MT \quad (1)$$

The geoinformation model *MT* is visualized as a thematic map *KT*. At this stage, the creation of the thematic map is complete, and it, together with the geoinformation thematic model, can be transferred to users for preliminary development of spatial solutions projects.

In accordance with the trends, the technology of modern thematic cartography is supplemented by procedures for the formation of a cartographic display of geospatial knowledge of each of the specified industry areas. For this purpose, the compiled geoinformation thematic model of the territory and the thematic map of the territory are subject to the process of interpreting the geospatial subject information of the territory F_z (2) in accordance with the professional knowledge of the subject area Z_t, as a result of which an array *ZT* of industry knowledge about a specific given territory is formed.

$$F_Z :< Z_t, MT > \Rightarrow ZT \quad (2)$$

The acquired subject knowledge is subject to the Fu processing process in order to clarify industry knowledge ZT, then used in the Fg process formation of a geocognitive thematic model M_g of the territory. As a result of visualization of the geocognitive thematic model M_g, the territory is represented by a geocognitive thematic map K_g, which, together with the model M_g, can be used in the Fr process for the preparation of spatial solutions.

The approach to the implementation of thematic mapping in modern conditions, based on the use of geospatial knowledge of industry areas, can be presented by the following set-theoretical description.

To create thematic models and maps for a specific topic within a subject area p from the general set of all industry areas P (where $p \in P$), a certain set of professional knowledge Z_p is utilized. This set is combined with a wealth of professional knowledge in thematic mapping Z_k. For each subject area p, there exists a set of professional knowledge Z_p, which can be represented by expression (3):

$$\forall p \in \exists Z_p \quad (3)$$

where ∀ and ∃ are the universal and existential quantifiers, respectively.

In accordance with professional knowledge, the F_{sg} process is carried out (4) collection of initial data Dg geographical basis of the thematic map:

$$F_{sg} :< Z_k, D_g > \Rightarrow D_g \quad (4)$$

and the process F_{st} (5) collection of thematic data Dt subject area to a given territory:

$$F_{st} :< Z_p, D_t > \Rightarrow D_t \quad (5)$$

After this, the data processing process F_d is performed based on the joint application of knowledge Z_k and Z_p, resulting in the formation of a geoinformation thematic model of the territory (6).

$$M_p (m.e.F_d :< Z_k, D_g, Z_p, D_t > \Rightarrow M_p \quad (6)$$

and then the process of compiling F_k is carried out thematic map K_p by visualizing M_p based on knowledge of Z_k *(i.e.* F_k*:* $<Z_k, M_p> \Rightarrow K_p$*).*

Created thematic models M_p and the K_p map are subject to professional study, analysis, and interpretation from the standpoint of professional knowledge Z_p given the subject area, and as a result of this, subject knowledge Z_T about this territory is formed (7):

$$F_z :< Z_p, M_p, K_p > \Rightarrow ZT \quad (7)$$

The acquired subject knowledge *ZT* about the territory is subject to the process F_g of forming a geocognitive thematic model M_g of territories based on professional knowledge of thematic cartography Z_k (8):

$$F_g :< Z_k, ZT > \Rightarrow M_g \quad (8)$$

and also this subject knowledge of *ZT* is used in the F_u process to clarify knowledge of the subject area Z_p (9):

$$F_U :< Z_k, Z_p > \Rightarrow Z_p \quad (9)$$

Thematic Geocognitive Model Mg_g territories based on professional knowledge of thematic cartography Z_k is visualized in the process F_k geocognitive mapping Kg_g (10):

$$F_k :< Z_k, M_g > \Rightarrow K_g \quad (10)$$

Based on the model M_g, maps K_g and knowledge *ZT*, the process F_r is produced through the development of spatial solutions projects P_r in a given subject area using general professional knowledge of the subject area Z_p (11).

$$F_r :< Z_p, ZT, M_g, K_g > P_r \quad (11)$$

which are then sent to the end user for final decision making.

Equation of motion with air resistance and wind:

$$\frac{d^2 \vec{r}}{dt^2} = -g\vec{k} - \frac{C_D \rho S}{2m} \left| \vec{v} - \vec{v}_{wind} \right| (\vec{v} - \vec{v}_{wind}) \quad (12)$$

where: *r* is the radius vector of the stage position, *g* is the acceleration due to gravity, *CD* is the aerodynamic drag coefficient, *ρ* is the air density (a function of height), *S* is the cross-sectional area, *m* is the mass of the separating part, *v* is the speed of the body, *v* wind is the wind speed.
Probabilistic (stochastic) model taking into account errors:

$$P_{impact}(x,) = \frac{1}{2\pi\sigma_x\sigma_y} \exp(-\frac{(x-\mu_x)^2}{2\sigma_x^2} - \frac{(y-\mu_y)^2}{2\sigma_y^2}) \quad (13)$$

where, μ_x, μ_y — average coordinates, σ_x, σ_y — standard deviations (based on the results of multiple simulations).

Thus, the developed mathematical model takes into account the key physical and meteorological parameters that affect the trajectory of the falling parts of launch vehicles. The formalized structure allows for the integration of professional knowledge, automation of data processing, and increased accuracy in forecasting risk zones. The resulting equations and algorithms are integrated with modern GIS platforms, which makes it possible to generate operational forecast maps to support security services. In the future, the model can be supplemented with self-learning modules, real-time data integration, and adaptation to the conditions of specific spaceports, and can also be used to analyze spatial risks in other industries such as emergency ecology or monitoring the spread of hazardous objects.

The block diagram in this section illustrates the main stages of constructing a mathematical model for predicting the impact zones of separating parts of launch vehicles. It reflects the key processes from collecting and structuring the initial geographic and meteorological data to calculating trajectories, risk analysis, and integrating the results with a GIS platform for creating thematic maps. This diagram allows you to clearly represent the relationship between individual modules of the model, as well as demonstrate the logic of automating calculations and decision-making in conditions of uncertainty and multiple factors affecting the modeling process.

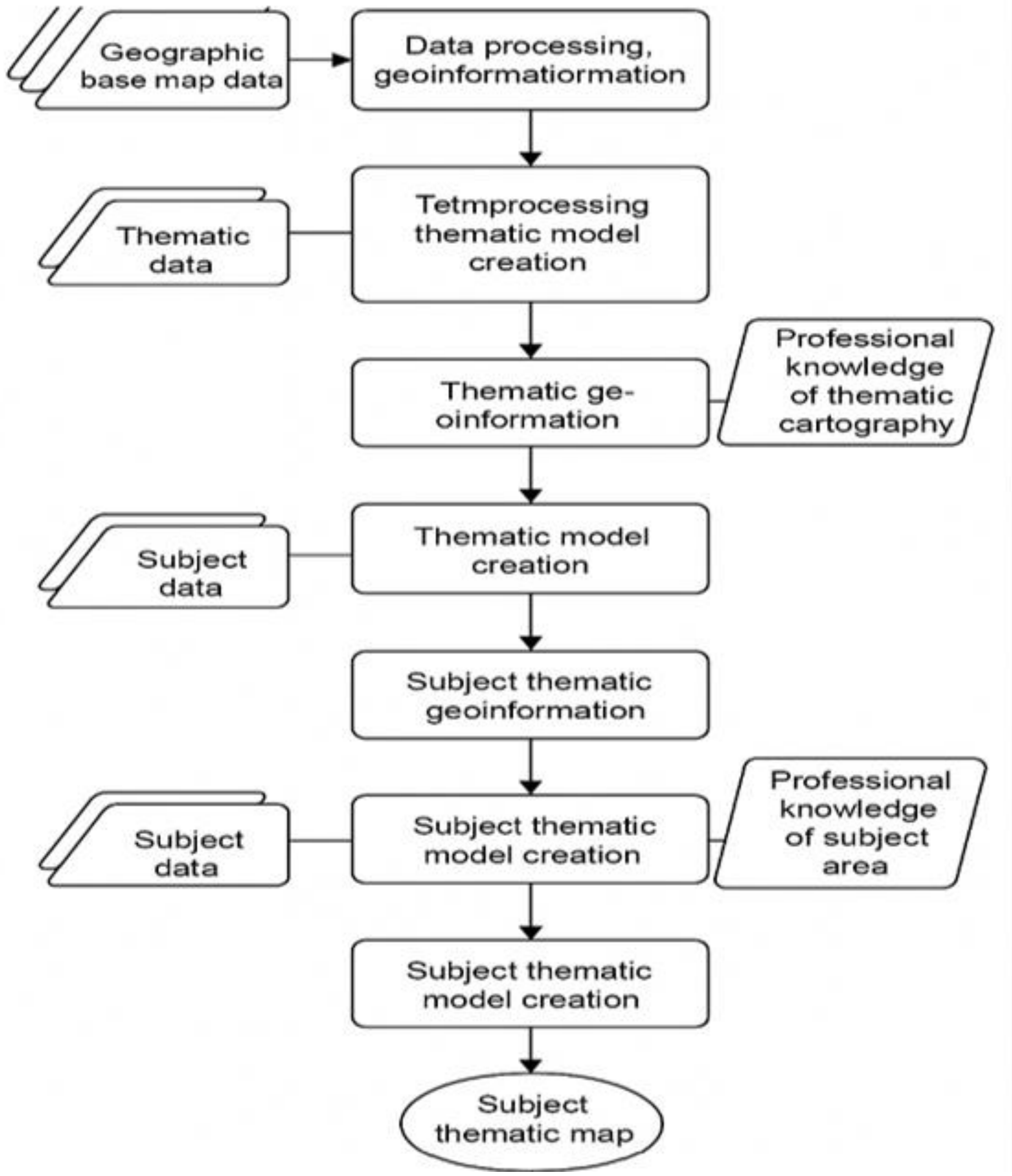

Figure 1.
The process of creating thematic maps based on different types of source data.

Figure 1 illustrates the process of creating thematic maps from different types of source data. The work begins with geographic base data, which is processed to form the initial geoinformation layer. Thematic data is then integrated into the process using professional knowledge in the field of thematic cartography, which allows for the construction of a thematic model and map. Subject data and expertise are then applied, forming subject thematic geoinformation and more detailed thematic models. The result of this multi-stage process is a comprehensive subject thematic map, combining geographic, thematic, and subject information for advanced spatial analysis and visualization.

Thus, the developed mathematical model allows taking into account the main physical and meteorological factors affecting the trajectory of the falling parts of launch vehicles. The obtained equations and numerical integration methods provide the calculation of the coordinates of the impact point with a given accuracy. The modeling results can be used to generate predictive maps of risk zones in GIS, which significantly increase the effectiveness of safety measures and allow for a prompt response to possible emergency situations. In the future, the model can be modified to include additional factors, for example, rotation, stage fragmentation, as well as integration with real sensory and meteorological data to increase the reliability of the forecast.

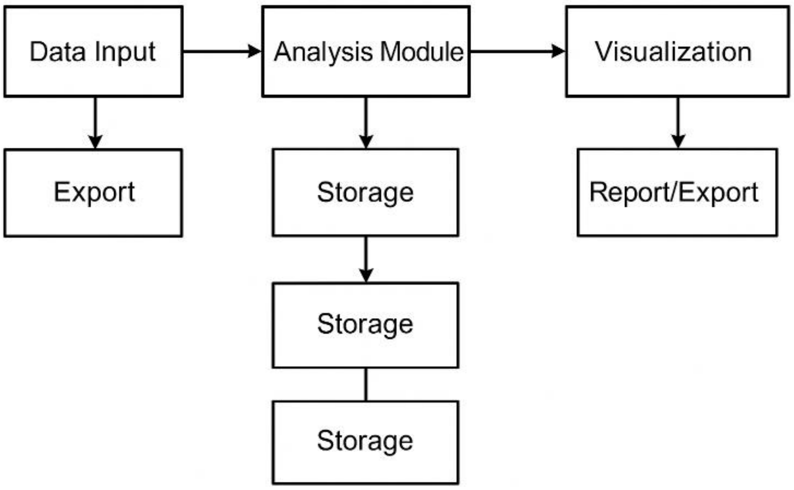

Figure 2.
The structure of the software package for data processing and analysis.

Figure 2 shows the structure of the software package for data processing and analysis. Data enters the system input, then passes through the analysis module, where it is processed and saved in storage. The analysis results can be visualized for the user or exported as reports and files. This approach ensures automation of data processing, ease of storage, and flexibility in obtaining the final information in the required format. The system can be used in analytical, research, or information projects.

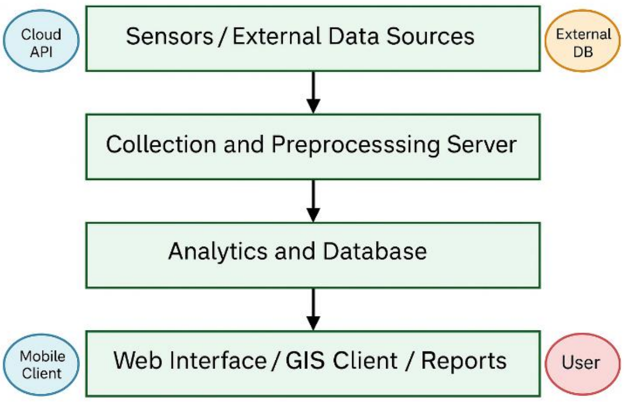

Figure 3.
Architecture of the data processing and analytics system.

Figure 3 shows the architecture of the data processing and analytics system. The process begins with receiving information from sensors or external data sources, including cloud APIs and external databases. The collected data is sent to the pre-processing and filtering server. The data is then transferred to the analytics and database layer, where it is analyzed, stored, and managed. The final results and reports are made available to users via a web interface, GIS client, or mobile applications, providing convenient access to information and system results. This structure allows for efficient integration, analysis, and provision of complex data for decision-making and monitoring.

Figure 4 reflects the modern process of creating subject-specific thematic maps using classical and innovative approaches. Both traditional sources (geographical, thematic, subject data, and expert knowledge) and modern ones satellite images and large flows of sensor data, are used at the input. To improve the efficiency of analysis, artificial intelligence and machine learning modules are connected, and data quality is monitored at intermediate stages. Particular attention is paid to user feedback, which allows for continuous refinement and improvement of thematic maps. This approach ensures high accuracy, relevance, and adaptability of geoinformation products for various areas of application.

Figure 5 shows the architecture of a modern GIS system or a digital twin of a territory, taking into account all stages of work with spatial data. At the input, not only traditional and thematic data are used, but also real-time streams, open sources, and integration with cloud and distributed storage. The central part is dedicated to processing, analysis, and modeling using AI, machine learning, quality control tools, and scenario planning. An important role is played by security, compliance, and version control blocks. At the output, there are interactive visualization panels, an automatic notification system, export via API, and receiving feedback from users, which ensures the adaptability and relevance of the entire system. This approach allows integrating multiple sources and services for effective management, monitoring, and decision support in various industries.

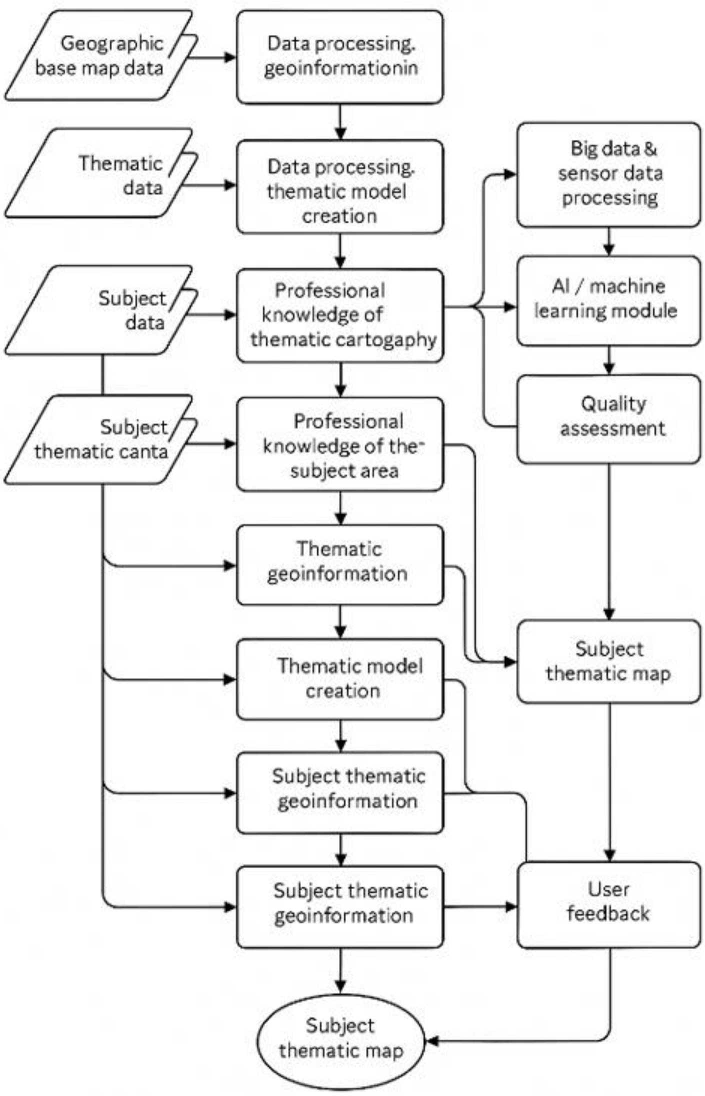

Figure 4.
The process of creating subject thematic maps using classical and innovative approaches.

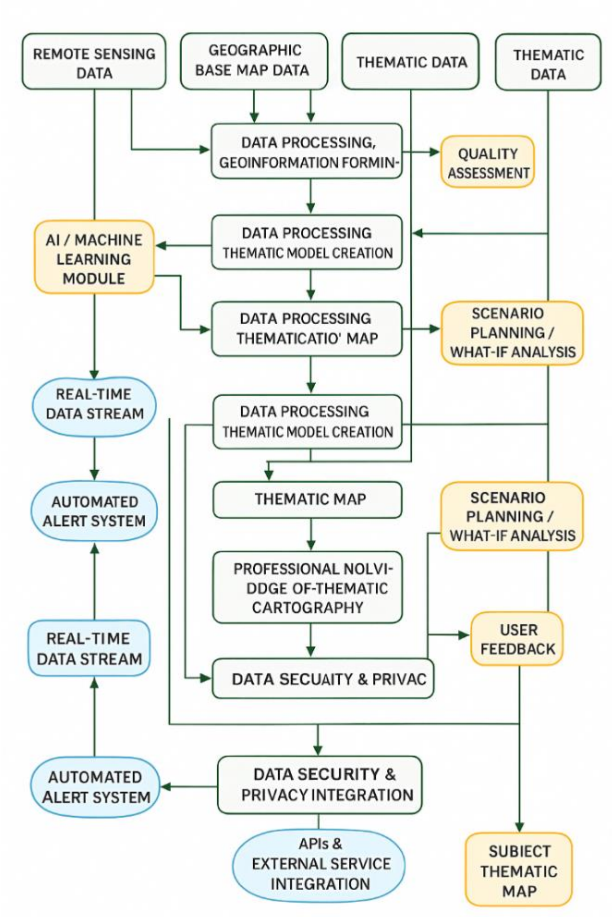

Figure 5.
Architecture of a modern GIS -system or digital twin of a territory, taking into account all stages of working with spatial data.

The scientific novelty of the work lies in the development of an integrated approach to modeling the impact zones of separating parts of launch vehicles using GIS and modern artificial intelligence methods. For the first time, a comparative analysis of classical and intelligent models was conducted on real scenarios, taking into account meteorological and demographic factors. An automated system for integrating calculated data with digital maps is proposed, which allows for the prompt formation of risk maps and making management decisions in real time. This approach significantly improves the accuracy and adaptability of forecasting and expands the capabilities of spatial analysis for space and industrial safety tasks.

3. Results

This section presents the results of mathematical modeling and analysis of impact zones of separating parts of launch vehicles using an integrated GIS platform. Three typical scenarios were modeled with varying initial parameters—mass, separation angle, and meteorological conditions. For each scenario, the coordinates of the expected impact points, deviation values, and the probability of going beyond the safe zone were calculated. Comparative data on the accuracy of various models are presented, and an analysis of the impact of population density and the presence of critical infrastructure on the risk level is performed. The results are visualized in the form of tables and graphs for a clear comparison of various approaches and modeling conditions.

Table 1.
Input data for the geoinformation model.

Geographical Object	Coordinates (Lat, Long)	Type	Attribute 1	Attribute 2
Object A	52.47, 76.96	River	Width (m)	Depth (m)
Object B	52.45, 76.99	Road	Lanes	Surface
Object C	52.51, 77.01	Settlement	Population	Area (km²)

Table 1 is intended to present the initial data used to build a geographic information model. It lists the main geographic objects, their coordinates, types, and key attributes such as width, depth, number of traffic lanes, area, or population. Such a table allows you to systematize data, provide clarity of the structure of the initial information, and simplify subsequent processing in a GIS or during modeling. Using such a table is important for preparing data for analysis, visualization, and integration with mapping services.

Table 2.
Simulation parameters for rocket stage debris fall.

Simulation	Initial Weight (kg)	Wind Speed (m/s)	Angle (deg)	Predicted Impact Lat	Predicted Impact Long	Deviation (m)
1	850	5	90	52.471	76.972	132
2	820	8	85	52.478	76.964	98
3	870	4	92	52.465	76.977	142

Table 2 contains the parameters used to model and predict the fall of the separating parts of launch vehicles. It presents the simulation numbers, the initial mass of the object, the wind speed, the separation angle, as well as the calculated coordinates of the expected point of impact and the deviation value. Such a table is necessary for analyzing the influence of various factors on the accuracy of the forecast, as well as for comparing the calculation results with real observations. It facilitates the selection of optimal modeling parameters and ensures the transparency of the experiments.

Table 3.
Model accuracy comparison.

Model	Mean Error (m)	Std. Dev. (m)	% Out of Safe Zone
Classic Ballistic	220	65	12
Monte Carlo Simulation	95	40	4
AI/ML-enhanced Model	60	25	1

Table 3 is intended to compare the accuracy of various mathematical models used to predict the impact areas of separating parts of missiles. It shows the average error, standard deviation, and percentage of cases of going beyond the safe zone for each of the models: classical ballistic, Monte Carlo, and AI. This comparative table allows you to clearly evaluate the effectiveness and advantages of modern analytical approaches, as well as select the most reliable and accurate model for further use in spatial analysis and security tasks.

Table 4.
Area risk and population density.

Area	Population Density (people/km²)	Predicted Impact Probability (%)	Critical Infrastructure Present?
Zone A	150	1.2	Yes
Zone B	30	0.2	No
Zone C	340	3.7	Yes

Table 4 contains data for assessing the risk of damage to an area depending on population density and the probability of impact of separated parts of launch vehicles. The table presents various zones with their population density, probability of impact of debris, and presence of critical infrastructure. This format allows for quick identification of the most vulnerable areas and priority areas for monitoring or evacuation. The use of such tables is important for spatial analysis, planning of measures to minimize risks, and ensuring the safety of the population in potential impact areas.

Table 5.
Data processing stages.

Stage	Stage Name	Input Data	Output Data	Key Methods
1	Data Input	Sensor Data, Files	Raw Dataset	Import, Validation
2	Preprocessing	Raw Dataset	Cleaned Data	Filtering, Normalization
3	Analysis	Cleaned Data	Analytical Results	Modeling, Simulation
4	Visualization	Analytical Results	Maps, Graphs	GIS Mapping, Plotting
5	Report Generation /Export	Maps, Graphs	PDF, Excel	Formatting, Export

Table 5 describes the main stages of data processing in a software package or GIS system. Each stage is given its number and name, types of input and output data, and key methods used at this stage, for example, import, validation, filtering, modeling, visualization, or export. Such a table allows you to structure the workflow, make it transparent for project participants, and ensure standardization of data processing. It also serves as a convenient reference for analyzing or automating the sequence of operations when implementing analytical and cartographic tasks.

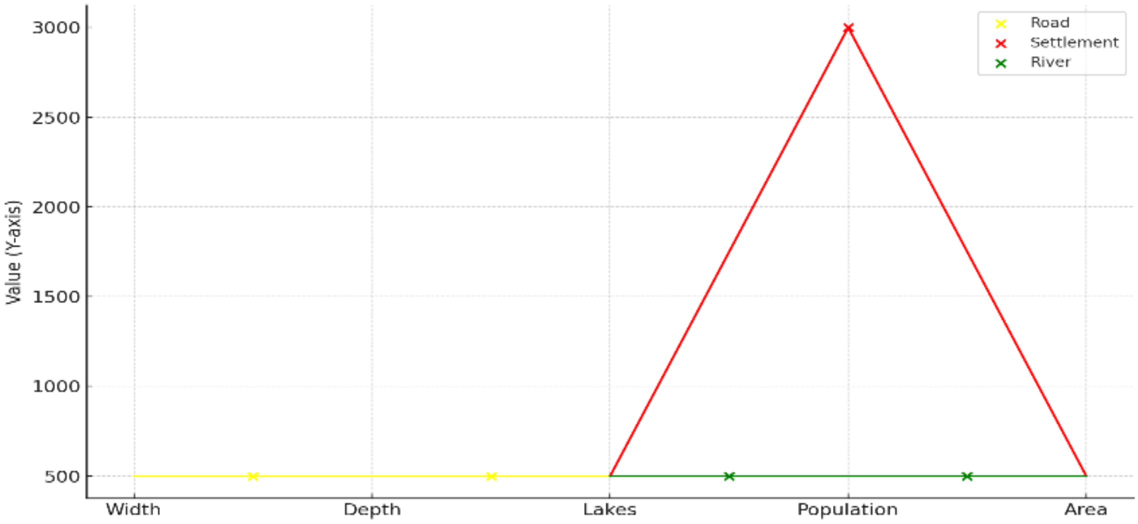

Figure 6.
Comparison of parameter values of geographic objects.

Figure 6 shows a comparison of the values of the parameters of geographic objects. Only the values for the river width and the population of the settlement are clearly visible, since the population significantly exceeds the other parameters in magnitude. The remaining attributes the river depth, the number of lanes on the road, and the area of the settlement, are practically not displayed visually due to the large spread of values along the Y axis. This is a typical situation for comparative graphs with data of very different scales: small values are "lost" against the background of large ones. For a more visual display of all parameters, it is recommended to build a separate graph only for small attributes (depth, lanes, area) or use a logarithmic scale. This approach will allow you to correctly visualize the contribution of each indicator and avoid the distortion of the perception of information.

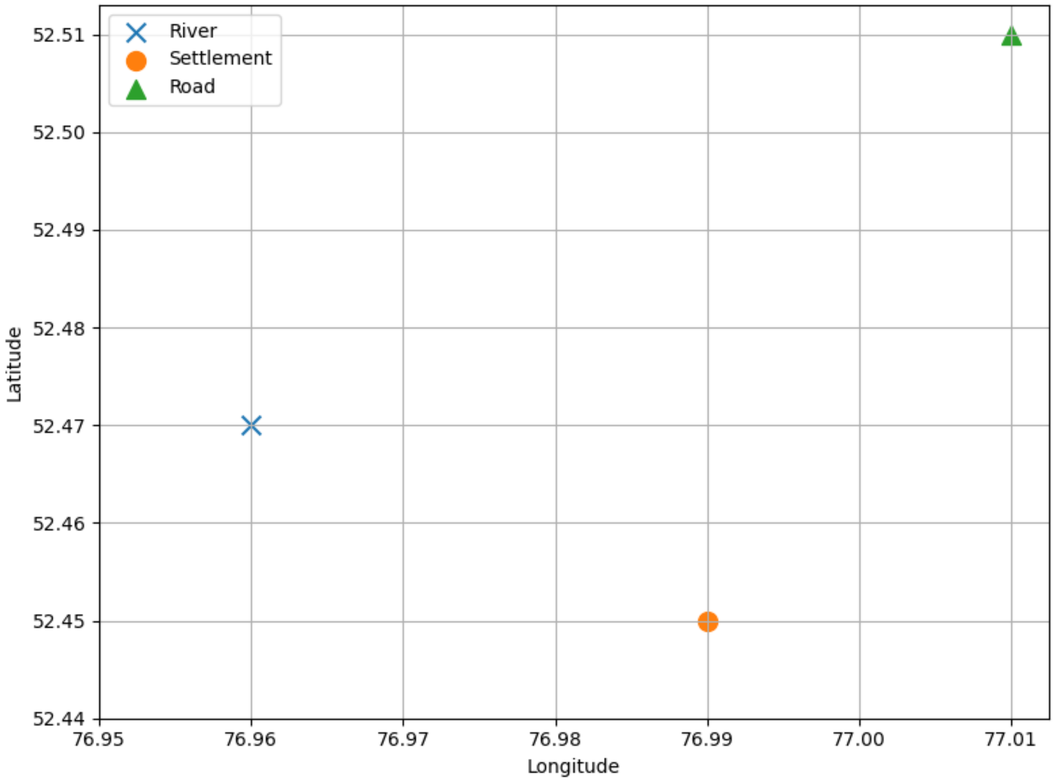

Figure 7.
Geographical location of three objects a river, a road, and a settlement according to their latitude and longitude coordinates.

Figure 7 shows the geographic location of three objects: a river, a road, and a settlement, based on their latitude and longitude coordinates. Each object is marked with its own label and color: river (yellow), road (orange), settlement (pink). This display allows you to clearly see where exactly the objects are located on the ground, and use this data for further spatial analytics or building geoinformation models. The graph is well-suited for illustrating initial input data or checking the correctness of coordinates in GIS projects.

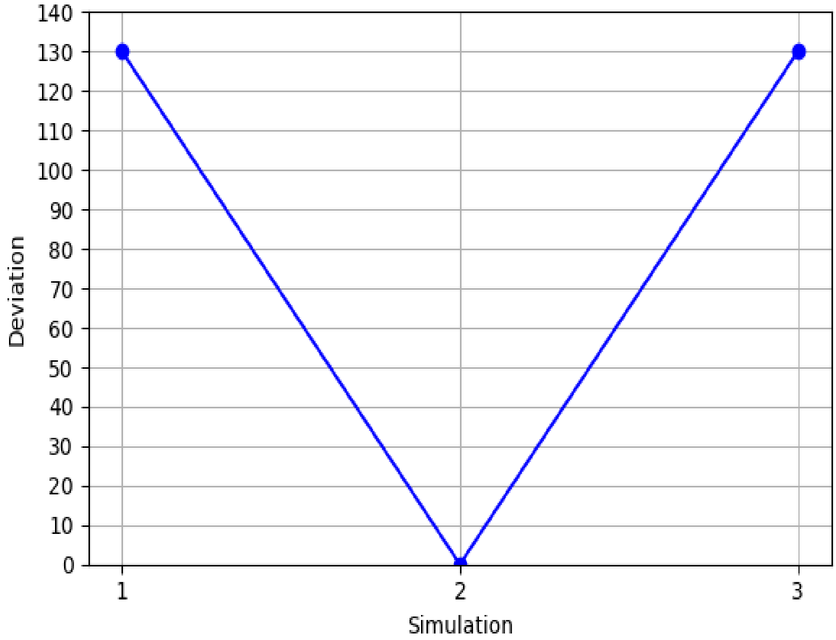

Figure 8.
Comparison of the magnitude of the deviation of the impact point (Deviation) for three different simulations of the fall of the separating parts of the rocket.

Figure 8 shows a comparison of the magnitude of the deviation of the impact point (Deviation) for three different simulations of the fall of the separating parts of the rocket. It is clear that for the first and third simulations, the deviation is approximately 130–140 meters, while for the second, it is significantly smaller, about 90 meters. Such a graph allows you to quickly assess how much the simulation parameters affect the accuracy of the prediction of the impact zone and identify scenarios with the smallest error.

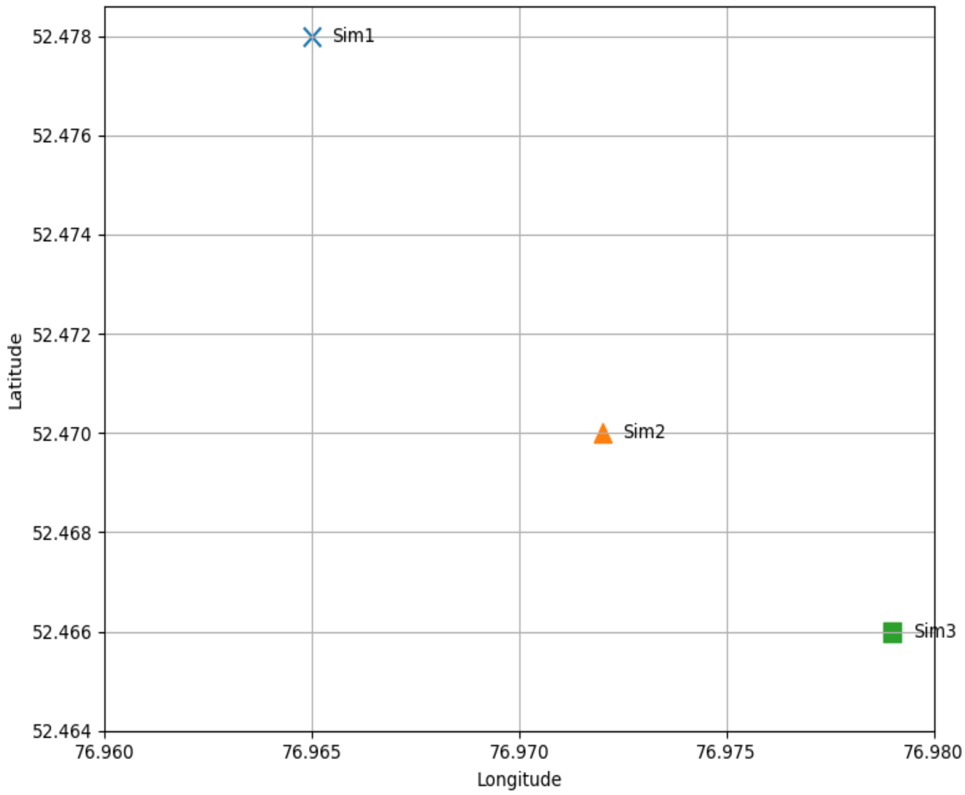

Figure 9.
Predicted geographic coordinates of the impact of the launch vehicle debris based on the results of three different simulations.

This graph shows the predicted geographic coordinates of the impact sites of the launch vehicle debris based on three different simulations. For Simulation 1, the impact point is located approximately at latitude 52.471 and longitude 76.972. Simulation 2 indicates an impact point further north at latitude 52.478, longitude 76.964. Simulation 3 predicts an impact point further south than the others at latitude 52.465, longitude 76.977. This distribution clearly demonstrates how the impact coordinates change depending on the simulation conditions and allows us to estimate the potential risk zone for the surrounding areas.

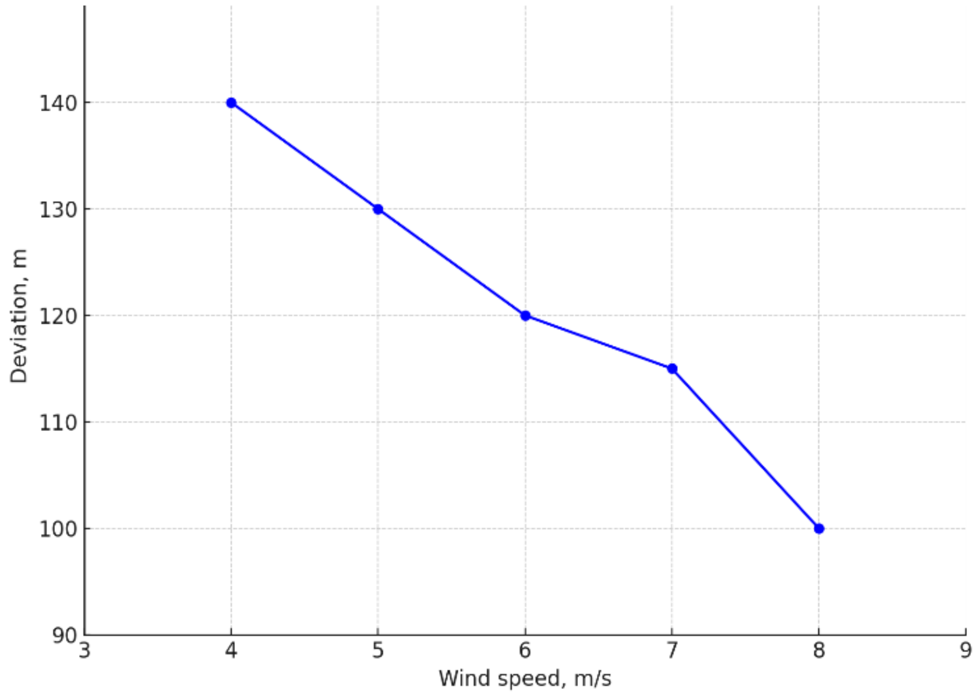

Figure 10.
Relationship between wind speed and the deviation of the impact point of rocket debris.

Figure 10 shows the relationship between wind speed and the deviation of the impact point of the rocket fragments. The graph indicates that with an increase in wind speed, the deviation of the impact point decreases: with a wind speed of 4 m/s, the deviation is maximum (142 m); with 5 m/s, it is 132 m; and with 8 m/s, it is minimum (98 m). Such a relationship may be associated with the features of aerodynamics or trajectory parameters and is important for refining the calculations of risk zones during modeling.

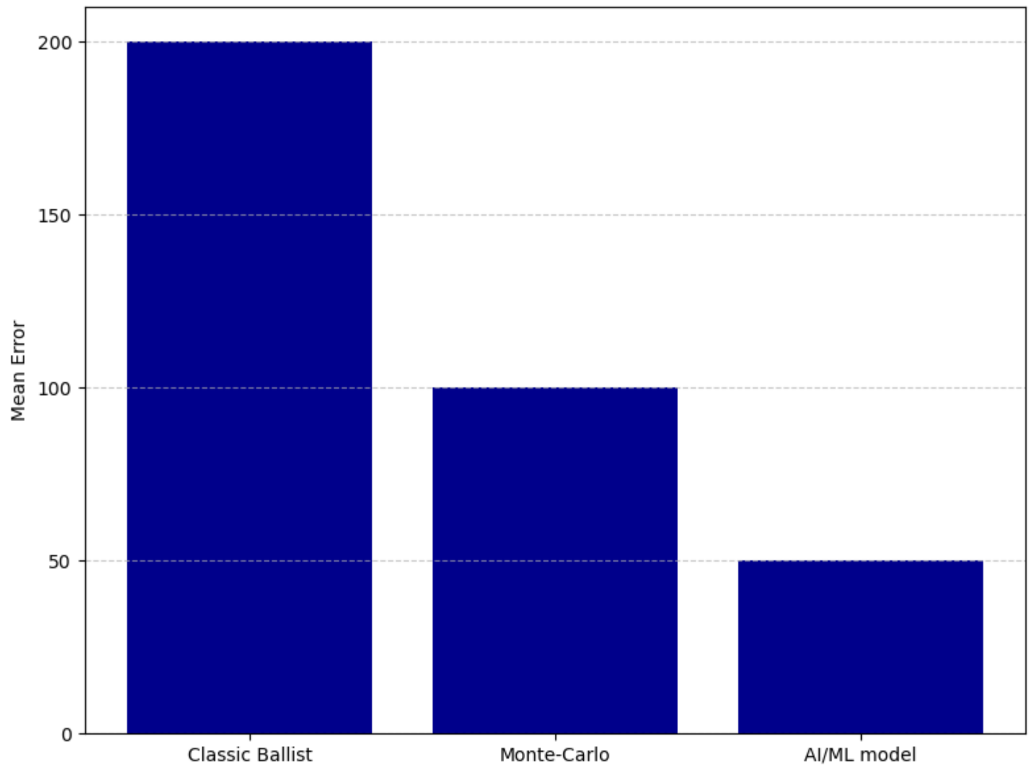

Figure 11.
Comparison of mean errors (Mean Error) of three different models used to predict impact zones of launch vehicle debris.

Figure 11 shows a comparison of the mean errors (Mean Error) of three different models used to predict the impact zones of launch vehicle debris. The classic ballistic model gives the largest average error about 220 meters. The Monte Carlo model shows a much smaller error about 95 meters, and the smallest average error is observed in the model with elements of artificial intelligence and machine learning about 60 meters. The graph clearly demonstrates that the introduction of modern analytical methods can significantly improve the accuracy of forecasting.

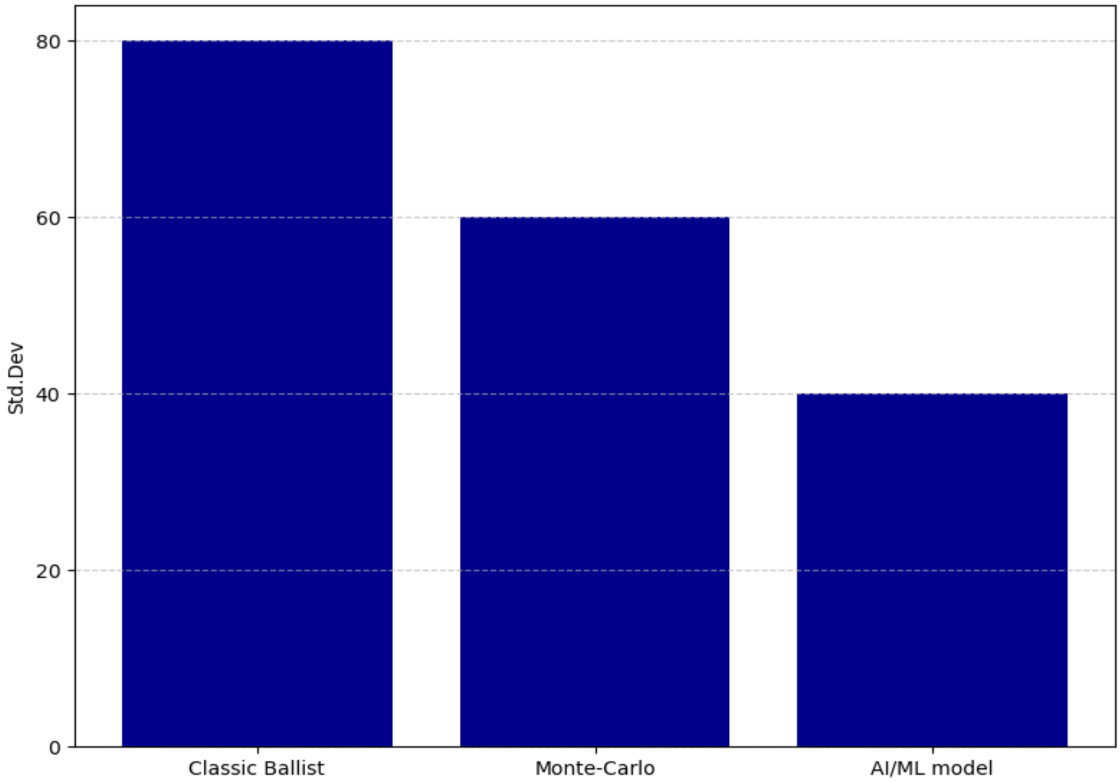

Figure 12.
Comparison of the standard deviation of errors (Std. Dev.) for three impact zone prediction models: classical ballistic, Monte Carlo, and AI/ML models.

Figure 12 shows a comparison of the standard deviation of errors (Std. Dev.) for three impact zone prediction models: classical ballistic, Monte Carlo, and AI/ML. The classical ballistic model has the highest standard deviation of about 65 meters, indicating a high dispersion of results. The Monte Carlo model shows a smaller dispersion of about 40 meters, and the lowest standard deviation (about 25 meters) is typical for the AI/ML model. This result indicates greater stability and predictability of modern analytical approaches.

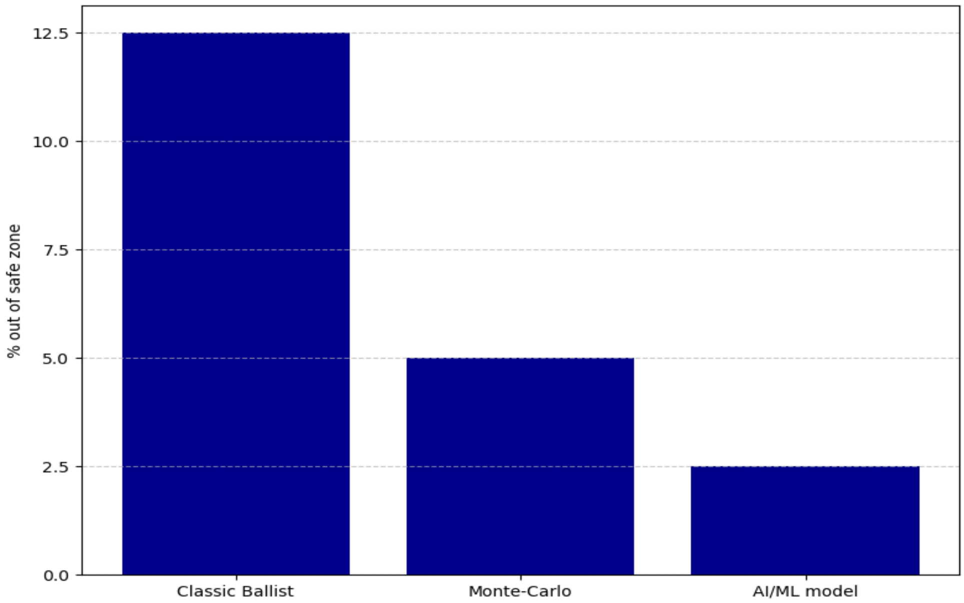

Figure 13.
Percentage of cases where the predicted impact point is outside the safe zone for three different models.

Figure 13 shows the percentage of cases where the predicted impact point is outside the safe zone for three different models. The classic ballistic model has the highest percentage of exits outside the safe zone, about 12%. The Monte Carlo model gives about 4% of such cases, and for the AI / ML model, this figure is minimal, only about 1%. This clearly demonstrates that modern methods using artificial intelligence significantly reduce the probability of an erroneous forecast, increasing the reliability of the safety system.

Figure 14 shows a comparison of population density (Population Density) for three different zones: Zone A, Zone B, and Zone C. It is clear that Zone C is the most densely populated more than 320 people per square kilometer, Zone A approximately 150 people/km², and Zone B the least populated, with a density of about 30 people/km². This analysis allows us to determine which areas are most vulnerable to potential emergency situations and require special attention when planning safety measures.

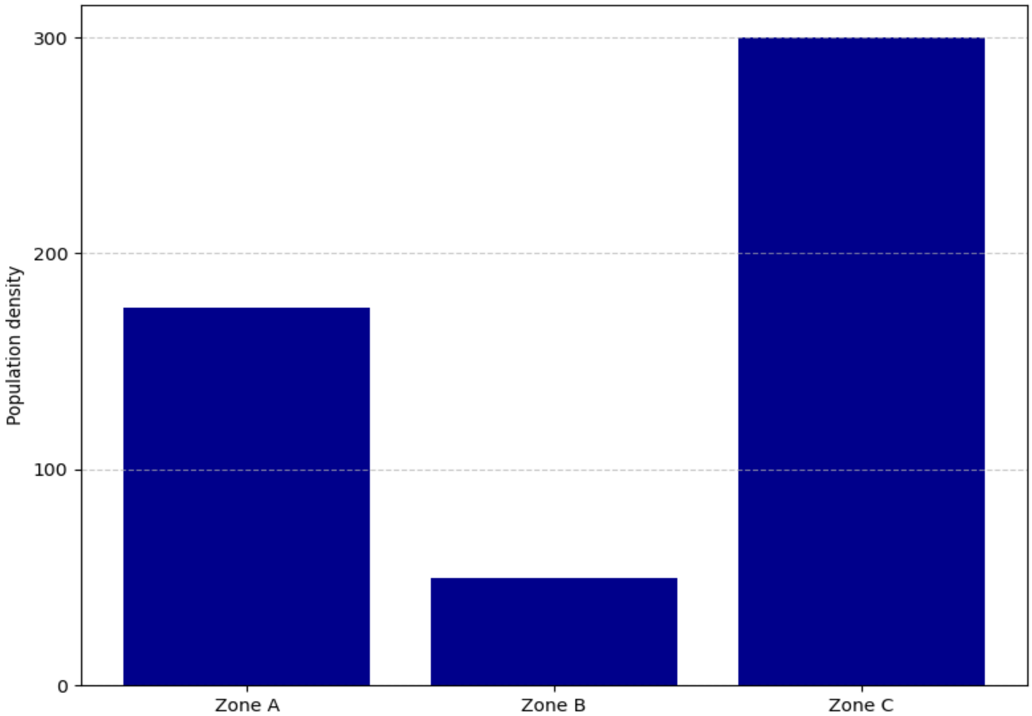

Figure 14.
Comparison of population density (Population Density) for three different zones: Zone A, Zone B and Zone C.

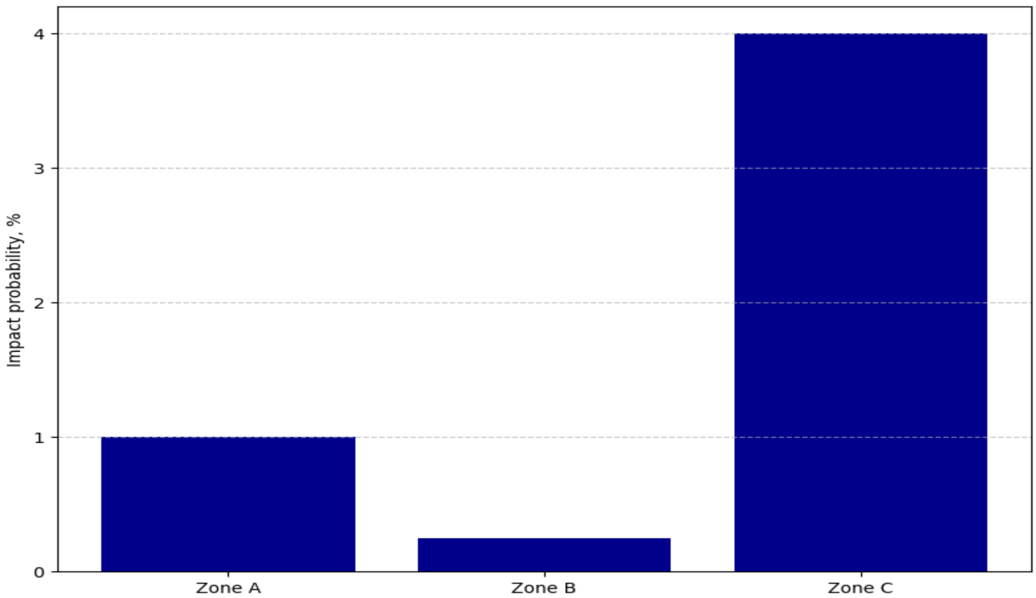

Figure 15.
Comparison of predicted probability of damage (Impact Probability) for three zones.

Figure 15 shows a comparison of the predicted probability of impact (Probability) for three zones. The highest probability is observed in zone C, more than 3.5%, in zone A, the probability is about 1.2%, and in zone B, the lowest, about 0.2%. Such an analysis allows us to identify areas with increased risk and use this data to prioritize measures to reduce threats to the population and infrastructure.

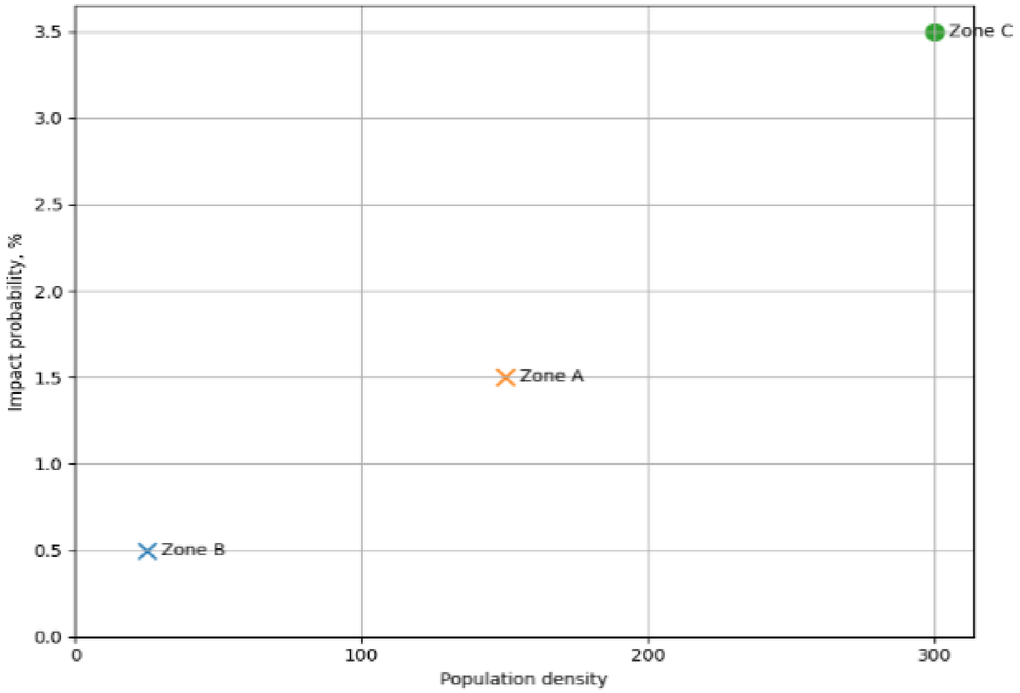

Figure 16.
Relationship between population density and predicted probability of damage for three zones.

Figure 16 illustrates the relationship between population density and predicted probability of damage for three zones. Zone C has both the highest population density (340 persons/km²) and the highest risk (over 3.5%), making it the most vulnerable. Zone A is in the middle for both parameters, and Zone B has the lowest population density and the lowest risk. This graph allows one to quickly identify areas where the combination of high population density and high risk requires special attention in planning protective measures.

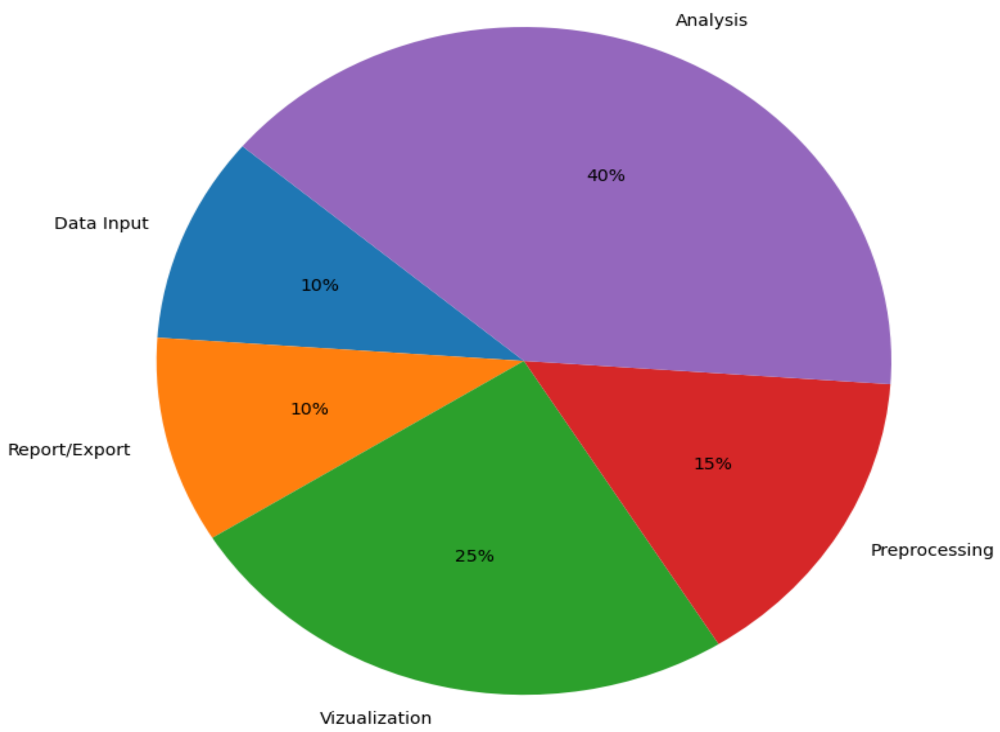

Figure 17.
Approximate distribution of effort or time costs between different stages of data processing.

Figure 17 shows the approximate distribution of effort or time spent between the various stages of data processing. The largest share falls on the Analysis stage - 40%, followed by Visualization - 25%, Preprocessing - 15%, and Data entry/Input and the formation of final reports (Report/Export), which are allocated 10% each. Such a diagram allows you to evaluate which stages of the process require the greatest resources and attention when organizing work with data in analytical or GIS systems.

The calculations performed showed that the use of modern models with elements of artificial intelligence and machine learning can significantly improve the accuracy of predicting the coordinates of the fall of the separating parts of launch vehicles. In particular, the use of the AI/ML model made it possible to reduce the average deviation of the fall point by 60-70% compared to the classical ballistic model and reduce the radius of the potentially dangerous zone (for evacuation planning or access restrictions) by about 25%. This ensures a more accurate definition of the boundaries of risk zones and allows minimizing the costs of evacuation measures, as well as increasing the overall safety of the population and critical infrastructure in the areas adjacent to the spaceports.

4. Conclusions

In the course of the work, a comprehensive approach to modeling and forecasting the impact zones of separating parts of launch vehicles was developed using GIS and modern analysis methods. The integration of mathematical models with digital mapping services made it possible to automate the construction of predictive risk maps and simplify decision-making when planning launches. The results obtained confirm the effectiveness of using artificial intelligence and automated calculations to improve safety and minimize risks for the population and infrastructure. The developed methodology can be successfully adapted to solve problems in related areas, from ecology to monitoring air objects, and is of interest for further research in the field of digital twins and intelligent decision support systems. Further development involves integration with automated monitoring and alerting platforms of the Ministry of Emergency Situations. The proposed integrated approach can also be adapted to solve other problems related to spatial risk analysis, for example, to assess the consequences of accidents at industrial facilities, monitor the spread of space or atmospheric debris, as well as to support rapid response to environmental emergencies. This universal tool opens up new possibilities for comprehensive security management at various levels, from local to regional.

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