

INTEGRATED MATHEMATICAL AND GEOSPATIAL APPROACH FOR CARGO AIRSHIP SITE SELECTION UNDER EMERGING EASA STANDARDS AND NATIONAL REQUIREMENTS

Petr POLÍVKA ^{1✉}, Petr PLÍVA ², Vladimír KOVAŘÍK ², Ivo DRAHOTSKÝ ¹

¹*Faculty of Transport Engineering, University of Pardubice, Pardubice, Czech Republic*

²*Faculty of Military Technology, University of Defence, Brno, Czech Republic*

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Abstract. The recent resurgence of Lighter-Than-Air (LTA) technologies presents a transformative opportunity for the logistics sector, particularly for transporting oversized cargo to infrastructure-limited regions. However, a significant research gap exists regarding the formalized ground infrastructure requirements for large-scale airships under emerging regulatory frameworks. This study proposes a novel, GIS-based multi-criteria methodology for selecting cargo airship operating sites, specifically aligned with the forthcoming European Aviation Safety Agency (EASA) regulations, including NPA 2025-04 and SC-GAS. The methodology transforms fragmented legislative and technical constraints into a mathematical Suitability Index comprising geometric, terrain, environmental, and legislative parameters. The framework was validated through a pilot case study in the Pardubice Region, Czech Republic, utilizing high-resolution digital elevation models (DMR 5G) and topographic datasets (Data50). Results demonstrate that the model effectively distinguishes between highly constrained urban-peri-urban environments and permissive rural-agricultural zones. By applying obstacle clearance buffers, slope thresholds, and focal statistics for area sizing, the workflow identified candidate sites capable of accommodating circular operating footprints up to 500 m in diameter. This modular approach provides a transparent, repeatable decision-support tool for regional screening, bridging the gap between abstract regulatory drafts and practical operational planning for the next generation of heavy-lift airships.

Keywords: lighter-than-air (LTA), cargo airships, site selection, GIS, EASA regulations, multi-criteria decision making (MCDM), logistics infrastructure, central Europe.

✉ Corresponding author. E-mail: petr.polivka1@student.upce.cz

1. Introduction

The logistics and aviation sectors are currently witnessing a significant resurgence of interest in Lighter-Than-Air (LTA) technologies. Modern cargo airships are increasingly recognized for their potential to provide substantial cargo capacity and unique operational capabilities compared to traditional means of transportation. Unlike conventional aircraft, these vehicles are particularly advantageous for transporting extremely heavy and bulky loads to locations where traditional transportation infrastructure is either non-existent or inefficient. Consequently, the operational scope of these airships is expanding into three primary domains:

- Transport to remote and infrastructure-limited areas,
- innovative models of urban and regional logistics,
- and the transport of oversized cargo.

Despite the technological maturation of airship prototypes, a critical gap remains regarding the ground infrastructure required to support these operations. While the

selection of landing sites for helicopters is governed by well-established international standards, such as the NATO standardization agreement STANAG 2999 (North Atlantic Treaty Organization [NATO], 2012), the regulations governing the landing of transport airships have not yet been elaborated to a comparable extent. This presents a significant challenge, as modern airships currently under development range in size from 100 to approximately 300 meters. The logistical ideal of “Door-to-Door” transport, which eliminates the need for transshipment, is frequently constrained by these spatial and technical limits, necessitating the precise identification of suitable operational areas located outside established airports.

The primary scientific challenge addressed in this study is the methodological fragmentation of the current regulatory environment. Although the European Aviation Safety Agency is expected to issue unified operational conditions through the Notice of Proposed Amendment (NPA) (European Aviation Safety Agency [EASA], 2025) and certification documents such as SC-GAS (EASA, 2022a) or

CS-30T/N (European Aviation Safety Agency, 2024), these emerging international drafts remain decoupled from specific national legislative frameworks. Currently, no unified analytical framework exists to synchronize heterogeneous data domains into a quantitative spatial model. This research gap creates an unresolved scientific problem: how to transform disparate, evolving qualitative norms into a standardized mathematical index for automated territory screening.

Building on this integrative need, this study moves beyond basic geospatial modelling toward a rigorous mathematical formalization of operational requirements. Previous research (Kovářík et al., 2025) has demonstrated the feasibility of using geospatial tools, such as ArcGIS Pro ModelBuilder, to automate the search for helicopter landing sites based on terrain slope and obstacle distances. The objective of this article is to bridge this gap by transforming complex legislative and technical constraints into formalized mathematical functions. By proposing a modular suitability index, the study provides a transparent and repeatable decision-support tool for the next generation of heavy-lift airship infrastructure planning.

2. Literature review

2.1. State-of-the-art in LTA logistics and operational requirements

The renaissance of LTA technology has transitioned from theoretical feasibility studies to specific industrial applications. While early literature focused broadly on economic viability in remote regions (Prentice & Thomson, 2003; Prentice & Knotts, 2014), recent scholarship has pivoted toward niche, high-value logistics where conventional transport modes fail. Specifically, contemporary studies have validated the utility of hybrid and rigid airships for transporting oversize/overmass cargo, such as power transformers for grid resilience (Tomasik, 2025) and time-sensitive cold chain logistics for agriculture (Ferro et al., 2024).

A critical distinction in modern LTA literature is the technological crossroad between “Hybrid” and “Rigid/VTOL” designs, which dictates infrastructure requirements. Hybrid architectures, such as the Lockheed Martin LMH-1, rely on aerodynamic lift and require Short Take-Off and Landing (STOL) operations, necessitating runway-like clearways (Lobner, 2024; Prentice & Ahmed, 2017). Conversely, rigid designs like the LCA60T (Flying Whales) emphasize stationary hovering capabilities for load exchange without landing, utilizing winching systems to mitigate the need for extensive ground handling infrastructure (Lobner, 2024; Paz et al., 2022).

Despite these operational advantages, the economic integration of airships remains contingent on quantifying their value proposition. Neal and Koo (2020) argue that demand modelling must account for “willingness to pay” for time savings and reliability, not just direct transport costs. Furthermore, the operational resilience of these

vehicles in disaster relief scenarios, specifically in Small Island Developing States and infrastructure-poor regions has been highlighted as a key differentiator from maritime and road transport (Paz et al., 2022; Tatham et al., 2017). However, widespread adoption is currently stalled by a “risk-averse market” waiting for certified operational frameworks (Lobner, 2024).

2.2. Methodological approaches to infrastructure site selection

The selection of suitable sites for transport infrastructure is a complex spatial problem typically addressed through Multi-Criteria Decision Making (MCDM), often coupled with Geographic Information Systems (GIS). Such approaches have been applied across various transport domains, utilizing hybrid GIS-MCDM models for refugee camp siting (Younes et al., 2022) or Fuzzy AHP frameworks for air cargo infrastructure location (Lakshmanan et al., 2024).

In the specific context of aviation, recent literature has been dominated by the siting of vertiports for Urban Air Mobility (UAM) and small Unmanned Aerial Systems (UAS). Lu et al. (2025) proposed a systematic framework for vertiport site selection, combining a modular grading-based evaluation system for initial screening with a location-allocation optimization model. Their methodology prioritizes safety, economic, and social dimensions through a hierarchical index system. Within this framework, they introduced an improved “progressive coverage model” (PCM-DSL) that integrates a demand satisfaction variable to address the trade-off between service coverage and equitable access in resource-constrained urban settings.

From a methodological standpoint, the Analytic Hierarchy Process (AHP) and its fuzzy extensions remain the dominant tools for weighting conflicting criteria. For instance, Evci et al. (2025) utilized a hybrid AHP-TOPSIS approach to locate UAV depots for healthcare logistics, prioritizing criteria such as distance to hospitals and meteorological conditions. Recent frameworks, such as Lakshmanan et al. (2024), successfully applied Fuzzy AHP to prioritize air cargo infrastructure locations, emphasizing techno-economic and operational criteria. However, these studies primarily address conventional fixed-wing cargo terminals rather than the unique aerostatic and geometric constraints of large cargo airships.

2.3. Current siting methodologies and regulatory constraints

The regulatory landscape for LTA operations is currently in a state of flux. While established frameworks exist for conventional aviation, regulations for modern airships are fragmented. Prentice et al. (2009) noted early on that the lack of specific certification standards created significant barriers to entry. Recently, EASA has moved to close this gap with the Prototype Technical Specifications for the Design of VFR Vertiports (PTS-VPT-DSN) (EASA, 2022b). While this document provides critical definitions for the

“D-value” (reference dimension) and obstacle limitation surfaces, it is primarily calibrated for small VTOL-capable aircraft (Enhanced Category) rather than large tonnage airships. While recent studies have extensively utilized MCDM and GIS for Urban Air Mobility (UAM) and small drone vertiport selection (e.g., Evci et al., 2025; Lu et al., 2025), these methodologies are inapplicable to large cargo airships due to fundamental differences in scale and operational physics. Unlike eVTOLs with D-values under 15 meters, cargo airships such as the LCA60T or LMH-1 range from 80 to 150 meters in length. Furthermore, airships require specific “operating sites” that must accommodate significant aerostatic inertia and susceptibility to wind. Certification criteria such as SC GAS (EASA, 2022a) give us the minimum resistance of the airship to weather conditions for landing, and for crane operations from a hover it is according to CS 29 (EASA, 2023), which is for helicopters.

2.4. Summary of literature review

A critical review of the current state of the art confirms that MCDM and GIS methodologies are widely applied to Urban Air Mobility and small drone vertiports. However, these models are inherently limited when they are applied to heavy-lift airships. The analysis of existing literature reveals a systematic deficiency because current geospatial models focus either on urban micro-climates for small systems or on conventional logistics. These approaches do not account for specific LTA vehicles requirements. Furthermore, the lack of a formalized bridge between the technical specifications in EASA drafts and the strict spatial requirement in national legislation remains a barrier to practical implementation. This situation reinforces the need for the integrative mathematical approach proposed in this study. This approach moves beyond simple obstacle detection to provide a unified suitability assessment tailored to the operational reality of cargo airships.

3. Analysis of operational requirements

Given the identified research gap and the fragmented nature of current legislation, this study bases its operational analysis specifically on the forthcoming EASA harmonization documents and legislative restrictions in the Czech Republic. Although the full framework of EASA is expected in 2026+ horizon.

3.1. EASA requirements

Regarding the definition of ground infrastructure, the key document is the NPA 2025-04 (EASA, 2025), which introduces the concept of “operational sites”. Although this document is in the draft stage, its requirements are considered authoritative for future logistics operations planning. This regulation explicitly requires a designated person to survey the operational site and create an “Operations Site Manual”. The suitability assessment is grounded in the definition of an “operating site”. In addition, the NPA

refers to certification requirements that have not yet been approved, such as SC-GAS and CS30T/N.

For terrain suitability modelling, the parameters this manual must contain are crucial. These include the overall dimensions of the operating site, the location and height of relevant obstacles affecting approach and take-off, and surface structure accounting for seasonal changes. This legislative requirement directly determines the necessity of using geospatial data for automated obstacle detection and terrain morphology analysis. For small VTOL vehicles, legislation allows landing without surveying the landing site, but this does not apply to large cargo airships. These vehicles must always land on pre-surveyed areas and, in the case of night landings, on properly lit areas.

Regarding the spatial requirements for the landing area, Specification CS-30T (EASA, 2024) allows for either circular or rectangular designs. The dimensions are formalized as follows:

- Area Length (Parameter *a*): This parameter is derived from the length of the runway, and ends at the stop of the take-off, to which is added the reserve distance. The reserve distance is given by the worst possible scenario, where there is either 100 m fixed reserve, 1.33 times the runway, or a failure at the decision point with a reserve of 60 m, a failure at the decision point with a multiple of 1.15, or an aborted take-off.
- Area Width (Parameter *b*): In the case of a rectangular area, this is defined as the airship’s width plus a safety margin of 200 m.

Reference points for commencing and terminating manoeuvres are defined at a height of 15 m above ground level, while the *decision point* is situated at a height of 60 m.

In addition to geometric parameters, environmental limits are incorporated into the model. Resistance to weather conditions is set in SC-GAS at a minimum of 10 kts (EASA, 2022a). Given the absence of specific standards for non-landing operations (hovering), requirements from the CS-29 regulation for large rotorcraft are applied, necessitating controllability in winds from any direction at a speed of at least 17 kts (EASA, 2023).

Maximal Ambient Atmospheric Conditions are not precisely defined but are required as part of certification and Operations Site Manual to determine performance data at operating temperatures, humidity, altitude, icing conditions, and wind speed (EASA, 2022a).

The maximum Terrain Slope and surface condition are addressed in the same manner, with the manufacturer required to document the maximum permissible slope for landing (EASA, 2022a, 2025).

3.2. National requirements

A significant constraining factor is also noise limits under Government Regulation No. 272/2011 Coll. (Collection of Laws of the Czech Republic, 2011), which establishes a limit of 60 dB per 16 hours for daytime and 50 dB per

8 hours for nighttime in protected outdoor spaces. For protected indoor spaces is a limit of 40 dB per 16 hours for daytime and 30 dB per 8 hours for nighttime. These hygienic limits represent a spatial constraint for locating landing sides.

Regulation No. 108/1997 Coll. (Collection of Laws of the Czech Republic, 1997) sets a minimum distance of 100 meters from residential buildings and requires a 50-meter safety zone around the operation to keep bystanders away.

Regulation L14 (Airports) (Ministry of Transport of the Czech Republic, 2025a) specifies Aircraft Classification Rating – Pavement Classification Rating (ACR-PCR) where are four classes of Subgrade Strength Categories:

1. High Strength, where the subgrade capacity is greater than or equal to 150 MPa (nominal 200 MPa).
2. Medium Strength, where the range is from 100 MPa (inclusive) to 150 MPa (nominal 120 MPa).
3. Low Strength, where the range is from 60 MPa (inclusive) to 100 MPa (nominal 80 MPa).
4. Ultra-low Strength, where the remaining subgrade has a bearing capacity below 60 MPa (nominal 50 MPa).

On the other hand, Regulation L14H (Heliports) (Ministry of Transport of the Czech Republic, 2025b) states that heliports are designed specifically for a Maximum Take-Off Mass (MTOM).

4. Methodology and mathematical formalization of operational integration

The formalization of operational requirements provides the theoretical basis for site selection. However, the practical application of these rules requires a hybrid workflow. This chapter details the algorithmic process of evaluating potential operating locations.

4.1. Hybrid assessment logic

The mathematical model is constructed as a hybrid system integrating two distinct types of constraints derived from the regulatory analysis:

1. Hard Constraints (Crisp Logic): These represent non-negotiable safety limits or legislative prohibitions. If a location violates a hard constraint, the suitability index (μ) immediately drops to 0. This ensures that the model never recommends an unsafe location, regardless of how favorable other parameters might be.
2. Soft Constraints (Fuzzy Logic): These represent operational parameters where conditions range from optimal to marginal. For variables such as noise levels, the model utilizes continuous linear functions normalized to the interval 0; 1. A value of 1 represents ideal conditions, while values approaching 0 indicate increasing operational risk or decreasing efficiency, though still within legal limits.

4.2. Algorithmic assessment workflow

The process begins with the formalization of landing area requirements. Once mathematically defined, these criteria are integrated into a GIS evaluation framework, utilizing geoprocessing tools to analyse datasets. Although GIS algorithms may diverge from legislative equations, all identified sites must strictly adhere to statutory suitability criteria. By applying masks and buffer zones over the Area of Interest (AOI), the system generates a suitability raster. The primary advantages of this approach are its simplicity and adaptability for cross-verification. However, as digital terrain models (DTM) often suffer from inherent inaccuracies, on-site physical inspection remains a critical component of the validation process.

4.3. Mathematical formalization of suitability

The transition from qualitative legislative requirements to a programmable geospatial model requires the strict formalization of operational constraints. This chapter will introduce a set of basic requirements, and the following chapter will create programmable equations for ArcGIS. While previous studies have utilized Model Builder to identify landing sites based primarily on terrain and obstacle attributes for helicopters (Kovářík et al., 2025), the operational profile of cargo airships in a civilian setting requires a more comprehensive assessment based on multiple criteria. This methodology introduces a Suitability Index (μ_{Land}). The results are defined in Equation (1) by multiplication of other parameters which represent specific requirements.

$$\mu_{Land} = \mu_{Shape} \cdot \mu_{Angle} \cdot \mu_{Terr} \cdot \mu_{Slope} \cdot \mu_{Res} \cdot \mu_{Noise} \cdot \mu_{Atm} \quad (1)$$

4.4. Landing area shape

Equation (2) introduces a selection criterion for determining a suitable area shape (μ_{Shape}), depending on the type of landing area. These areas are therefore either square (μ_{Sqr}) or circular (μ_{Circle}). If any shape is suitable, then:

$$\mu_{Shape} = \begin{cases} \mu_{Circle} \vee \mu_{Sqr} & \text{for } \mu_{Circle} \vee \mu_{Sqr} > 0, \\ 0 & \text{for } \mu_{Circle} \vee \mu_{Sqr} = 0. \end{cases} \quad (2)$$

Circular landing zone offers the highest operational flexibility, the suitability (μ_{Circle}) is derived from the available obstacle-free diameter (D_{clear}) relative to the required minimum parameter (a) derived from CS-30T, Equation (3) is:

$$\mu_{Circle} = \begin{cases} 1 & \text{for } D_{clear} \geq a, \\ 0 & \text{for } D_{clear} < a. \end{cases} \quad (3)$$

Rectangular landing zone (μ_{Sqr}) is based on same parameter (a) for length of landing area (L_{clear}), but second parameter (a) is for wide of landing zone (W_{clear}) with is derived also from CS-30T, Equation (4) is:

$$\mu_{Sqr} = \begin{cases} 1 & \text{for } W_{clear} \geq b < a \wedge L_{clear} \geq a, \\ 0 & \text{for } W_{clear} < b < a \vee L_{clear} < a. \end{cases} \quad (4)$$

4.5. Approach angle

Airships may have different requirements for approach angles (μ_{Angle}), and given the size of cargo airships, this logic is crisp in order to maintain safety over finding more landing sites. The mathematical formalization in Equation (5) compares the angle formed by the height of surrounding obstacles (H_{obs}) and their distance from landing site (D_{obs}) against the airship's maximum performance capabilities (α_{Max}) and minimum (α_{min}):

$$\mu_{Angle} = \begin{cases} 1 & \text{for } \alpha_{Max} \geq \arctan\left(\frac{H_{obs}}{D_{obs}}\right) \wedge \arctan\left(\frac{H_{obs}}{D_{obs}}\right) \geq \alpha_{min} \\ 0 & \text{for } \alpha_{Max} < \arctan\left(\frac{H_{obs}}{D_{obs}}\right) \vee \arctan\left(\frac{H_{obs}}{D_{obs}}\right) < \alpha_{min} \end{cases} \quad (5)$$

4.6. Terrain bearing strength

Modern hybrid airship designs such as the LMH-1 utilise Air Cushion Landing Systems (ACLS) (Lobner, 2024), allowing operations on unpaved surfaces like sand, snow, or water. Regulation L14 specifies four basic load-bearing ranges ($\{l_i\}_{i=1}^4$) with nominal PCR values ($p_{RWY,i}$). Depending on the manufacturer's requirements (p_{Ship}), the range within which the airship operates is determined in specific range, and nominal PCR value (p_{RWY}) of this range is then provided to assist in identifying suitable AOI shows in Equation (6):

$$p_{RWY} = \sum_{i=1}^4 p_{RWY,i} [p_{Ship} \in l_i]. \quad (6)$$

To ensure safe ground operations, the model should evaluate the mechanical properties of the landing site through the Terrain Bearing Strength Suitability function (μ_{Terr}). This parameter is critical for heavy cargo airships operating on unprepared surfaces where the risk of ground failure must be mitigated. Equation (7) defines this suitability by comparing the actual local Terrain Bearing Strength (p) against the PCR nominal value (p_{RWY}):

$$\mu_{Terr} = \begin{cases} 1 & \text{for } p \geq p_{RWY} \\ 0 & \text{for } p < p_{RWY} \end{cases} \quad (7)$$

4.7. Terrain slope suitability

Beyond soil mechanics, the morphological characteristics of the terrain are decisive for the stability of large aerostatic vehicles during ground operations. Equation (8) defines the aggregate Terrain Slope Suitability (μ_{Slope}) from actual slope (θ) and limit slope (θ_{Lim}). Since both the L14 and L14H are designed to land at airports or paved heliports, STANAG 2999 (NATO, 2012) will be applied to this item:

$$\mu_{Slope} = \begin{cases} 1 & \text{for } \theta \leq \theta_{Lim} \\ 0 & \text{for } \theta > \theta_{Lim} \end{cases} \quad (8)$$

4.8. Constant legislative buffer zones

In addition to legislative limits is a mandatory buffer zone (μ_{Res}) defined by Equation (9). This function is a crisp derived from national legislation governing off-field landings. The regulation mandates that operations must be conducted outside contiguous residential areas, establishing a minimum protective distance (d_{Res}) of from the nearest residential building. Consequently, any grid cell where the distance to the nearest dwelling (d_{Land}) falls below this threshold.

$$\mu_{Res} = \begin{cases} 1 & \text{for } d_{Land} \geq d_{Res} \\ 0 & \text{for } d_{Land} < d_{Res} \end{cases} \quad (9)$$

4.9. Noise legislative buffer zones

To integrate the airship into the logistics chain near populated areas, the model must account for noise emissions, adhering to hygiene limits defined in national regulations. The equivalent sound pressure level ($L_{Aeq,T}$) at a specific distance is calculated using the logarithmic attenuation formula, assuming a worst-case scenario without terrain shielding in Equation (10). Although there are shows source noise level measured ($L_{Aeq,Meas}$) reference distance (l_1), distance to the evaluated point (l_2), and duration of the operation (T_{Op}) with duration of daytime (T_{Ref}):

$$L_{Aeq,T} = L_{Aeq,Meas} + 10 \log_{10} \left(\frac{l_1^2 \cdot T_{Op}}{l_2^2 \cdot T_{Ref}} \right). \quad (10)$$

The resulting suitability (μ_{Noise}) ensures compliance with the limit values for outdoor ($L_{Aeq,T,O}$) and indoor ($L_{Aeq,T,I}$) protected spaces depending on the time of day (Equation (11)):

$$\mu_{Noise} = \begin{cases} 1 & \text{for } L_{Aeq,T} \leq L_{Aeq,T,I} \\ \frac{L_{Aeq,T,O} - L_{Aeq,T}}{L_{Aeq,T,O} - L_{Aeq,T,I}} & \text{for } L_{Aeq,T,I} < L_{Aeq,T} \leq L_{Aeq,T,O} \\ 0 & \text{for } L_{Aeq,T} > L_{Aeq,T,O} \end{cases} \quad (11)$$

4.10. Ambient atmospheric conditions

While previous landing zone suitability models acknowledged meteorological data as an auxiliary, it was not typically integrated directly into the core suitability equations for landing site selection. However, for large-volume LTA, environmental factors are critical go/no-go parameters. The environmental suitability index (μ_{Atm}) in Equation (12) is a composite of wind (μ_{Wind}), temperature (μ_{Temp}), altitude (μ_{Alt}), humidity (μ_{Hum}), and icing (μ_{Ice}) conditions:

$$\mu_{Atm} = \mu_{Wind} \cdot \mu_{Temp} \cdot \mu_{Alt} \cdot \mu_{Hum} \cdot \mu_{Ice}. \quad (12)$$

5. Practical implementation

For the purposes of practical demonstration, the full theoretical framework was implemented only partially. The proposed methodology defines a multi-criteria suitability

model for cargo airship operating sites, integrating geometric, terrain, legislative, and atmospheric constraints. However, a complete operational implementation would require detailed manufacturer-specific performance limits, validated ground-handling procedures, soil-bearing data, and temporally resolved meteorological inputs, which are not currently available in a sufficiently consistent form for the study area. In addition, no routine operational database of large cargo airships currently exists that would allow direct calibration of all model components under real conditions. The present implementation represents a pilot geospatial application of the framework, limited to criteria that can be consistently extracted from available topographic and elevation data and combined with selected legislative constraints.

The Pardubice Region was selected as a suitable pilot area because it combines a heterogeneous landscape structure within a manageable regional extent, including urbanized zones, transport corridors, industrial areas, agricultural land, and forested terrain. This enables the model to be tested under both highly constrained and relatively open spatial conditions using a consistent set of input data. In its current form, the practical implementation is a Czech case study focused on the Pardubice Region. Nevertheless, the overall methodological framework is intended to be transferable to other regions, provided that comparable geospatial datasets are available and that the relevant legislative and operational thresholds are adapted to local conditions.

5.1. Data and area of interest

The proposed methodology was applied to an area located in the Pardubice Region in the eastern part of the Czech Republic in order to partially verify the practical applicability of the mathematical model. The analysed area covers approximately 55×30 km (about 1650 km²), with its approximate centre located at coordinates E = 563291, N = 5539466 in UTM Zone 33N. The region represents a typical Central European landscape composed of urban settlements, industrial areas, agricultural land, forested zones, and transport infrastructure. This environmental heterogeneity makes the area suitable for testing the robustness of the proposed approach across different obstacle configurations and terrain conditions. For visual interpretation of the results, two detailed areas of interest, AOI 1 and AOI 2, were selected within the full computational extent, representing contrasting landscape settings (Figure 1). These two AOIs were not selected only for illustration purposes, but also as two contrasting practical implementation examples. AOI 1 represents a more urbanized and infrastructure-dense environment, whereas AOI 2 represents a more open rural-agricultural setting. Their comparison was used to assess whether the workflow produces consistent and transferable outputs under different landscape conditions. In Figure 1, the red frame delineates the full computational extent, while the blue

frames indicate the locations of AOI 1 and AOI 2 used for the detailed interpretation of the model outputs.

For the identification of surface obstacles and other relevant landscape features, the Digital Geographic Model of the Czech Republic (Data50) provided by the Czech Office for Surveying, Mapping and Cadastre was used. Data50 is a nationwide digital topographic dataset derived from the cartographic basis of the 1:50,000 Basic Topographic Map of the Czech Republic and contains 69 classes of geographic objects organized into thematic groups (Geoportal ČÚZK, 2025). The source data are distributed as individual vector layers in ESRI Shapefile (.shp) format. To improve the efficiency of the processing workflow, the entire dataset was imported into an ESRI feature geodatabase, which allowed more effective management of thematic layers and more efficient spatial analysis.

Terrain morphology was derived from the Digital Elevation Model of the Czech Republic, 5th generation (DMR 5G) (Geoportal ČÚZK, 2026). The DMR 5G dataset is based on airborne laser scanning and is distributed in compressed LAZ point-cloud format. For the purposes of terrain analysis, the original LAZ files were converted to LAS, subsequently transformed into a Triangulated Irregular Network (TIN) surface representation, and finally converted into a raster elevation model suitable for slope calculation and related terrain analyses. All processing steps were subsequently applied using the same input datasets, thresholds, and geoprocessing logic across the full study extent and both detailed AOIs. No AOI-specific parameter tuning was introduced. This ensures that differences between the outputs reflect differences in landscape structure rather than manual adjustment of the model. The transferability of the approach outside the Czech Republic is therefore conditional rather than automatic. While the general workflow can be applied more broadly, its practical implementation depends on the availability of equivalent input datasets, the interpretation of local or national regulatory requirements, and the adjustment of selected operational thresholds to the characteristics of a specific airship type and operational environment.

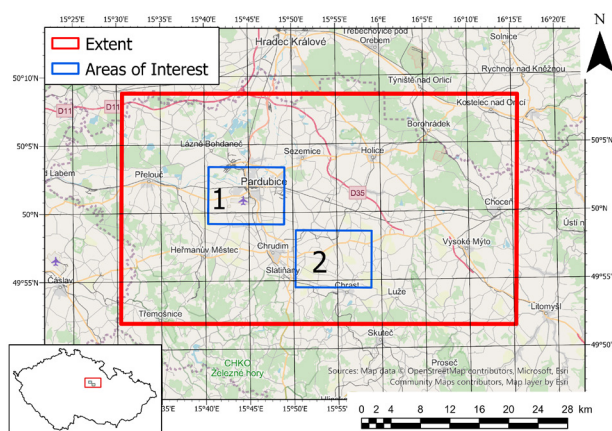


Figure 1. Study area and selected AOI's in the Pardubice Region, Czech Republic

5.2. Identification of suitable sites

The complete implementation logic is summarized in Figure 2. The workflow proceeds from vector obstacle extraction and DEM-derived terrain analysis to raster-based exclusion modelling and final focal-neighbourhood assessment of minimum operating-area diameter. Relevant obstacle features are extracted from the vector dataset, while terrain slope is derived from the DEM. Obstacle-clearance distances are calculated using the adopted approach/departure-angle criterion and subsequently converted into exclusion buffers. After rasterization, the obstacle and slope layers are combined into a binary suitability surface. Finally, circular neighbourhood analysis is used to determine the largest operating-area diameter that can be accommodated at each location, producing a categorical suitability map based on the available area size.

In the practical workflow, the most robust subset of criteria was implemented, namely obstacle-related clearance, minimum landing-area size, and terrain slope. The first step consisted of identifying obstacle features and estimating their spatial influence through the modified geometric relation derived from Equation (5) to Equation (13):

$$l = H_{obs} \frac{\sin(90 - \alpha_{min})}{\sin(\alpha_{min})}. \quad (13)$$

Equation (13) contains obstacle height (H_{obs}), the minimum admissible approach or departure angle (α_{min}), and the resulting horizontal clearance distance between the obstacle and a potential operating-site location (l). Based on available technical sources, the minimum operational angle (α_{min}) was approximated as 4.75° . The maximum angle (α_{Max}) was set to 90° , reflecting the simplifying assumption that the model is constrained primarily by the minimum admissible approach geometry. In the present implementation, only the minimum-angle constraint was used to derive the resulting clearance distances.

After calculating obstacle-specific distances, spatial buffers were generated around the identified features. These buffers represent areas where landing operations are considered unsuitable due to insufficient clearance. If the calculated distance exceeded 730 m, the value was capped at this threshold. This simplification was introduced to keep the implementation linked to the operational reference height 60 meters above ground where the landing phase begins within the adopted regulatory interpretation.

In the case of residential areas, a fixed buffer distance of 100 m was applied whenever the calculated value was smaller than this threshold. This step represents a simplified substitute for a more detailed legislative and opera-

tional treatment that could not be implemented due to insufficient input data.

A separate treatment was applied to abrupt terrain discontinuities. In this case, no buffer was generated, but the corresponding vector features were directly rasterized and integrated into the raster-based suitability workflow. More generally, all obstacle-related operations were initially performed in vector format and were then converted into raster layers for subsequent overlay and reclassification.

The final terrain-related dataset used in the implementation was the DEM-derived slope layer. Slope was calculated using the Slope tool and reclassified according to the STANAG 2999 threshold of 7° (NATO, 2012), above which the terrain was considered unsuitable. The obstacle and terrain layers were then merged into a single binary suitability surface, where value 0 indicates unsuitable space and value 1 indicates potentially suitable space. This binary raster can be considered an intermediate result of the model, as it does not provide operational approval for a specific airship, but rather identifies candidate areas for further assessment.

The final stage of the implementation evaluated the spatial extent of suitable areas using Focal Statistics with a circular neighbourhood. Circular areas with diameters ranging from 100 m to 500 m, in 50 m increments, were tested in order to determine how large an obstacle-free and slope-compliant area could be accommodated at each location. The outputs were subsequently reclassified into a final categorical layer. In this representation, value 0 denotes unsuitable areas, while values 1–9 correspond to progressively larger circular operating areas from 100 m to 500 m. Two contrasting practical implementations of the final suitability outputs are presented for AOI 1 in Figure 3 and for AOI 2 in Figure 4. In both figures, the colour classes indicate the diameter of the circular operating area that can be accommodated at a given location, whereas hatched areas represent locations classified as unsuitable. AOI 1 represents an urban–peri-urban environment near Pardubice, while AOI 2 represents a more open rural-agricultural landscape.

Taken together, AOI 1 and AOI 2 serve as two complementary implementation examples of the proposed workflow. The resulting maps reveal a clear contrast between the two analysed AOIs. In AOI 1, located in the more urbanized and infrastructure-dense environment near Pardubice, suitable areas are comparatively sparse, fragmented, and mostly confined to isolated open parcels at the urban fringe. Larger classes occur only locally, while the central built-up and transport-dominated parts of the AOI remain predominantly unsuitable. By contrast, AOI 2, situated in a more open rural-agricultural setting, contains a

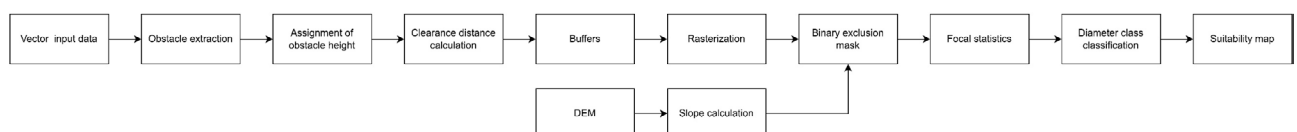


Figure 2. GIS-based workflow for cargo-airship operating-site suitability assessment

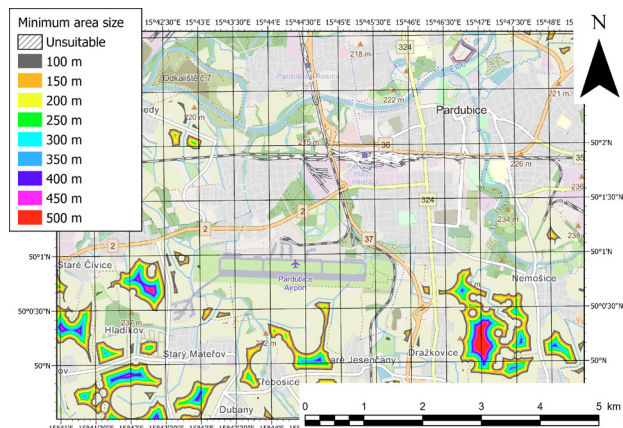


Figure 3. Cargo-airship operating-site suitability in AOI 1

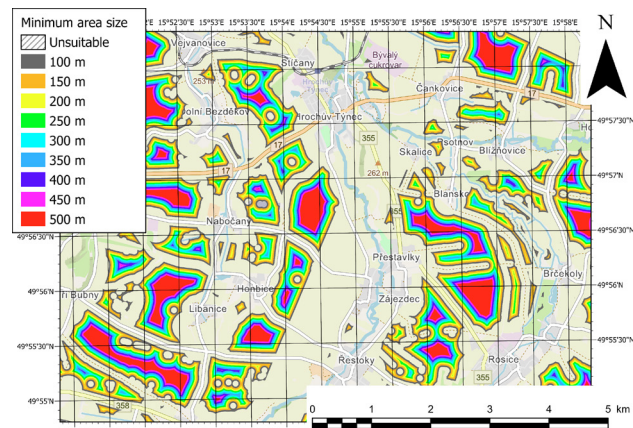


Figure 4. Cargo-airship operating-site suitability in AOI 2

Table 1. Quantitative comparison of suitability outputs for the two detailed areas of interest

AOI	Valid AOI area [km ²]	Unsuitable area [km ²]	Unsuitable area [%]	Potentially suitable area [km ²]	Potentially suitable area [%]
AOI 1	79.83	72.88	91.30	6.95	8.70
AOI 2	79.83	52.71	66.03	27.12	33.97

substantially higher number of candidate areas and several spatially extensive cores reaching the 400–500 m classes. The nested colour structure visible in both detailed outputs indicates that smaller suitable diameters occur more frequently, whereas the largest classes are preserved only in the central parts of broader open spaces. The outputs therefore not only distinguish suitable from unsuitable land, but also express the approximate operational scale that can be accommodated at each location.

Table 1 summarizes the area statistics for the two detailed AOIs after applying the obstacle-clearance, terrain-slope, and minimum-area criteria. The calculation refers only to the valid classified raster cells: masked and non-classified values were excluded. The results show a clear contrast between the two areas. In AOI 1, potentially suitable land accounts for only 8.70% of the valid area, whereas in AOI 2 it reaches 33.97%. This difference supports the interpretation that the workflow responds to variations in landscape structure and obstacle density.

Overall, the implemented workflow provides an initial geospatial screening of terrain potentially suitable for cargo-airship landing or take-off. The results should be interpreted as a preliminary decision-support product, intended to narrow the search space for subsequent operator review, field inspection, and more detailed mission-specific analysis.

6. Discussion

The primary contribution of this study is the translation of fragmented and heterogeneous regulatory constraints into a reproducible GIS workflow for large cargo airships. This research differs from existing site selection studies focused

on helicopters or urban air mobility by addressing the unique scale and aerostatic constraints of Lighter-Than-Air vehicles. The objective is not to identify final operating sites, but to demonstrate how selected technical and regulatory constraints can be formalized as spatial rules for regional pre-screening. In contrast to many GIS-based site-selection studies that rely primarily on weighted suitability scoring, the proposed methodology introduces a hybrid assessment logic that combines crisp and fuzzy constraints into a multiplicative suitability index. This mathematical formalization ensures that violating any hard safety limit immediately reduces the suitability score to zero regardless of other favourable parameters. The practical implementation demonstrates that applying this strict spatial exclusion based on obstacle clearance, terrain slope, and minimum area dimensions successfully achieves strong spatial differentiation.

A significant methodological challenge is the current absence of a reference database containing verified cargo airship operating sites. The model outputs presented in Figure 3 and Figure 4 show that the workflow responds clearly to differences in landscape structure. In the more urbanized Pardubice setting (Figure 3), candidate areas are fragmented and spatially limited, reflecting the constraining effect of buildings, transport infrastructure, and complex land-use geometry. By contrast, the more rural-agricultural setting (Figure 4) contains larger and more continuous potentially suitable areas. This comparison indicates that open agricultural landscapes provide better spatial preconditions for potential cargo-airship operations, while urbanized and infrastructure-dense environments substantially reduce the available candidate space.

The present implementation relies on several simplifying assumptions that define the current limitations of

the model. The reliance on circular focal neighbourhoods ensures computational efficiency for regional screening but simplifies the diverse geometry of real operating sites. Static obstacle buffers do not currently account for dynamic variables such as wind direction, approach alignment, or specific manoeuvring strategies like weathervaning and hover assisted cargo operations. Furthermore, the terrain slope threshold of 7° adopted from military standards serves only as a conservative proxy for terrain suitability. Future research should therefore replace this proxy with thresholds derived from Operations Site Manual for a specific airship type. Crucial operational parameters including atmospheric suitability, soil bearing capacity, and specific national noise regulations were omitted from the final computation. These factors cannot yet be represented with sufficient reliability using available public data and existing regulatory guidance.

The developed framework serves primarily as a preliminary decision support tool rather than a final certification product. Its principal strength is the efficient reduction of a large search space into a manageable set of candidate locations for subsequent expert review and field inspection. Although the practical implementation utilizes a Czech case study, the underlying methodology is highly transferable. The general workflow can be applied to other international regions if comparable topographic and elevation datasets are available. Future applications in different countries will require the reinterpretation of local legislative constraints and the adaptation of operational thresholds to match specific regional conditions.

7. Conclusions

This study proposed a GIS-based framework for the identification of potential operating sites for large cargo airships by translating selected operational and regulatory requirements into formalized spatial criteria. In contrast to existing site-selection studies focused mainly on helicopters, UAS, or urban air mobility, the presented approach addresses the scale and operational logic of heavy cargo airships and emphasizes the need to interpret operating-site suitability as a structured combination of geometric, terrain, legislative, and environmental conditions.

The practical implementation in the Pardubice Region was intentionally limited to the subset of criteria that could be reliably obtained from currently available geospatial data. Even under this reduced implementation, the model produced meaningful spatial differentiation between highly constrained urbanized terrain and more permissive rural-agricultural areas. The outputs showed that obstacle clearance, slope, and minimum area size are already sufficient to identify candidate locations and to distinguish between areas suitable only for small operating footprints and those that can accommodate larger circular areas up to 500 m. Although the practical implementation presented here is based on a Czech case study, the framework itself is designed as a transferable and modular approach whose broader applicability depends on the availability of

comparable data sources and the adaptation of regulatory and operational thresholds to local conditions.

At the same time, the results confirm that the current model should be regarded as a pre-screening and decision-support tool, not as a certification-ready operational method. The purpose is not to instruct a commander or pilot exactly where to land, but to provide an informed spatial overview of the operating environment and to indicate where more detailed assessment, field verification, and operational judgement should be concentrated.

A major strength of the framework is its modular design. Individual components of the model can be added, removed, or refined according to data availability, the characteristics of a specific airship type, the applicable national legislation, and the operational context. This makes the framework adaptable not only for emergency landing assessment, but also for broader planning tasks, such as regional screening, logistics studies, and future infrastructure support analysis.

A complete airship operating-site assessment will require the future integration of soil conditions, atmospheric constraints, noise effects, and airship-type-specific technical limits. Nevertheless, the modular design of the proposed framework provides a strong foundation for such future extensions. As the regulatory environment for large cargo airships matures and more detailed technical data become available, the proposed approach may evolve from a first-order screening tool into a more comprehensive operational site-assessment system.

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Author contributions

PP (Petr Polívka) and ID (Ivo Drahotský) conceived the study and were responsible for the design and development of the research framework. PP was responsible for the legislative analysis, mathematical formalization of the suitability index, and wrote the first draft of the article. PPL (Petr Plíva) and VK (Vladimír Kovařík) were responsible for data collection, geospatial processing in GIS environment, and the practical implementation of the case study. ID and VK provided supervision, performed data interpretation.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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