

Parametric Modelling and GIS Integration for Multi-Criteria Decision-Making: An Application to the Einstein Telescope Underground Research Infrastructure

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Abstract

This paper presents an advanced computational framework developed to support decision-making for the placement of the underground Einstein Telescope, a third-generation gravitational-wave observatory. The system aims to automate the search for an optimal location through a multi-criteria analysis approach. Because the ET is extremely sensitive to environmental noise sources—including seismic, thermal, and anthropogenic vibrations—its design prioritises underground construction. This strategy, also adopted for the Japanese KAGRA detector and in contrast to surface-based observatories such as LIGO and Virgo, minimises interference from surface activities while ensuring subsurface stability.

The proposed methodology integrates Geographic Information System (GIS) data, incorporating a Digital Surface Model (DSM) to spatially represent relevant factors. The dominant site-selection criteria were identified and weighted according to their scientific and strategic importance in collaboration with the ET scientific community. An interactive parametric model was developed to interface directly with the GIS data, enabling evaluation of key factors and providing real-time analytical feedback on placement scenarios. Using an evolutionary algorithm combined with a composite fitness function, the system balances competing objectives and delivers optimised solutions, offering a robust decision-support tool for the early planning stages of the Einstein Telescope project. Although the Sardinia site is currently considered a preliminary case study, the methodology is generalisable and applicable to other candidate sites to host ET.

1. Introduction

1.1 Einstein Telescope research infrastructure

Einstein Telescope (ET) is a proposed underground infrastructure to host a third-generation, gravitational-wave observatory. The project was included in the European Strategy Forum on Research Infrastructures roadmap (ESFRI, 2021) and is currently in its preparatory phase. ET community is a large, international network comprising over 50 research units worldwide. Numerous European countries are actively engaged in the initiative, with three candidate sites identified. These sites are now working in parallel to demonstrate the technical and financial feasibility of hosting the project. The evaluation process to determine the optimal geometry for achieving the highest scientific performance is still ongoing. The existing gravitational wave detectors, Advanced LIGO and Advanced Virgo, are located on Earth's surface, where seismic noise significantly limits their sensitivity below 10 Hz. ET as a European project for a next-generation GW detector, aims to enhance sensitivity by tenfold at these low frequencies. To tackle seismic noise, one innovative solution is to construct the detector underground. This approach could revolutionise gravitational wave detection.

ET builds on the success of current, second-generation laser-interferometric detectors, Advanced Virgo and Advanced LIGO, whose breakthrough discoveries of merging black holes (BHs) and neutron stars over the past 5 years have ushered scientists into the new era of gravitational-wave astronomy. An interferometer detects changes in the relative optical path length of laser beams travelling along orthogonal arms. In gravitational-wave detectors such as Virgo, LIGO, and the envisaged ET, a passing gravitational wave slightly stretches one arm while compressing the other, inducing a phase difference in the recombined beams at the beam splitter. This phase difference is

converted into an intensity variation at the photodetector, which is proportional to the strain induced by the wave. Third-generation instruments, like ET, will push this technique to its limits by combining longer arm lengths, cryogenic mirrors, advanced seismic isolation, and quantum-noise suppression techniques to achieve improvements in strain sensitivity (B. P. Abbott et al., 2016; R. Abbott et al., 2023; Buikema, 2020; Hild et al., 2011). ET will achieve a greatly improved sensitivity by being realised underground, increasing the size of the current generation of interferometers to overcome 10km arm length, and by implementing a series of new technologies. These include a cryogenic system to cool some of the main optics to 10 – 20K, new quantum technologies to reduce the fluctuations of the light, and a set of infrastructural and active noise-mitigation measures to reduce environmental perturbations.

The main research question of this study is how to effectively determine the placement of ET megastructure, considering its complex scientific, spatial and environmental constraints. Consequently, the primary objective is to develop and validate a parametric computational framework capable of optimising the spatial placement within a given candidate area.

1.2 ET candidate sites

Selecting the optimal place for the Einstein Telescope is a multifaceted process that requires balancing scientific and technical considerations with financial, political, and socio-economic factors (Amann et al., 2020). A key aspect involves determining the ideal underground position while accounting for constraints and potential sources of error that could impact sensitivity. The interplay of these factors adds complexity to the evaluation and decision-making process.

Site-characterisation studies are underway in the candidate sites, Sardinia (Italy) and Euregio Meuse-Rhine, to enable the optimal

site selection considering the feasibility of the construction and predict the impact of the local environment on the detector sensitivity and operation (Koley et al., 2022; Villani et al., 2024). A third potential site in the Lusatia Region, Germany, has recently been proposed, and teams have now joined efforts to advance the site preparation studies. The Italian proposal, led by the National Institute for Nuclear Physics (INFN), is planning to place ET in the area of the former Sos Enattos mine in Sardinia (Muccini et al., 2025). This decision rests on two complementary arguments tied to feasibility and pre-existing knowledge of the site (Naticchioni et al., 2020).

The official site selection process for the ET is governed by the Board of Governmental Representatives (BGR). It is the link with and between involved governments and funding agencies. The computational framework presented in this study is intended as a preliminary decision-support tool to assist scientific and engineering teams during this preparatory phase, rather than a definitive placement directive. Also, the framework focuses on 'spatial placement optimisation within a pre-selected candidate area, rather than macro-level regional site selection.

1.3 ET geometry configuration

According to Sathyaprakash et al (2012) the ET design study team concluded that a triangular topology is the optimal strategy to achieve the sensitivity goal of a third-generation. The arms of the triangle are each used twice to form three Michelson interferometers, as shown in Figure 1.

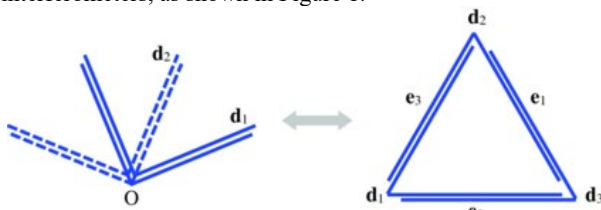


Figure 1 Triangular topology of ET, in which each arm of length L is used twice to form three detectors with a 60° opening angle, is equivalent to that of two L -shaped detectors of length $3L/4$, whose arms house two detectors each (Sathyaprakash et al., 2012)

Each V-shaped detector in the array has arms of 10 km in length, with an opening angle of $\alpha = 60^\circ$ and the detectors are rotated relative to each other by an angle of 120° . However, the discussion is still open in the scientific community about whether two L-shaped separated interferometers are a better option than one triangle. The recent study of Branchesi et al. (2023) conclude that both options (the 10 km triangle and a 15 km 2L) are valid. Their comparison shows that, from the scientific point of view, the solution of 2L of 15 km oriented at 45° relatively is superior on basically all the metrics that they have considered, except for the nominal sensitivity to stochastic backgrounds. However, they acknowledge that whatever layout is decided ET will overperform the network of 2nd Generation observatories at their best expected sensitivities by several orders of magnitude in all relevant metrics.

From a Construction, Civil Engineering and Technical point of view, the triangle option figures to be much more complex than the two L-shaped ETs since it includes two interferometer sides (laser tubes and related parts in every triangle segment).

1.4 Multi-criteria decision-making

The uncertainty in the ET infrastructure's geometry, coupled with site-specific constraints, creates a vast and complex solution

space that is difficult to explore without developing a specific tool to support decision-making actions. Given the interrelation of the variables (location, rotation, shape and multiple constraints), the civil engineering design team adopted a multi-criteria approach to connect the different aspects, analyse them and optimise the objectives. Multi-criteria analysis is a methodology that evaluates several factors in an integrated manner, instead of conducting different parallel or sequential evaluations considering a single or a few criteria at a time. It allows for a more comprehensive evaluation of alternatives and provides a stronger basis for decision making.

In the Architecture, Engineering, and Construction sector (AEC) is increasingly adopting algorithmic optimisation techniques to address complex decision-making challenges while supporting Multi-criteria decision-making (MCDM), leveraging advances in computational tools and methodologies. MCDM provides a structured and transparent framework to support planners by integrating diverse metrics and facilitating informed decisions.

MCDM is often combined with 3D parametric modelling, for a direct association to geometrical representation. By systematically varying these parameters, planners can assess a wide spectrum of scenarios, fostering a nuanced understanding of potential outcomes. This capability has proven invaluable in addressing the increasing complexity of modern construction projects, evolving from the idea of a single person activity to a multi-person activity, while adding complexity to the design process (Fischer et al., 2017). The AEC field, therefore, has seen a recent surge in the application of formal optimisation techniques to aid in Multidisciplinary building design and exploration (Muthumanickam et al., 2023).

Parametric models are adaptable according to the values of the parameters. An interesting approach to finding optimal values of these parameters in the search domain, which normally contains an infinite number of possibilities, is that of evolutionary computation (EC). EC algorithms are inspired by the principles of natural selection and biological evolution. EC algorithms maintain a population of potential solutions that evolve over time through genetic operators such as mutation and crossover. The selection mechanism identifies the most promising individuals in the population to reproduce, thereby generating new solutions with potentially improved fitness values (Khamis, 2024). This approach is particularly well-suited for complex, multi-modal, and non-linear problems like the placement of ET. Although the foundations of EC date back to the late 1950s, early progress was constrained by limited computational power and methodological shortcomings (Back, Hammel, and Schwefel, 1997). Today, the landscape has significantly evolved. Robust libraries supporting EC algorithms are available in multiple programming languages and commercial platforms (Yavan, Maalek, and Toğan, 2024). In AEC sector, particularly in 3D model-based planning, software platforms like Rhinoceros and Revit offer integrated or modular support for EC. These tools are especially popular among professionals due to their visual programming interfaces and extensible ecosystems, enriched by a vibrant user community. Evolutionary algorithms extend traditional approaches by enabling the simultaneous optimisation of multiple criteria. These range from simple linear aggregation methods to more sophisticated Pareto-based ranking techniques (Coello, Lamont, and Veldhuizen, 2007). However, EC techniques are not without limitations. Achieving optimal solutions often depends on the topology of the fitness landscape, and there is no guarantee of convergence to a global optimum within a finite time frame (Khamis, 2024; Rutten, 2013).

Evolutionary algorithms encompass different categories, depending on how and whether they address single-objective or multi-objective optimisation problems. In this work, we adopt a scalarisation approach for the optimisation problem as explained in the method paragraph (3.4).

2. Related works

From a civil engineering point of view, ET is a unique project and far from a typical infrastructure project from many points of view. On one hand, Stakeholders from the scientific part have very specific requirements to protect the project from the noise and fit their technical and optical network of tubes and suspension towers for the optical elements. On the other hand, there is in this first conceptual design study phase much undefined basic information to start from, like the shape, baseline configuration, location, or depth underground. However, there is a comparable project to ET in terms of size and complexity and comparable approaches to this work in terms of optimisation goals.

A comparable existing infrastructure is the European Organisation for Nuclear Research (CERN) particle accelerator in Geneva. CERN is conducting a similar study to host a new underground Structure in the Geneva area for the Future Circular Collider, which will be a tunnel of 97.75 km (Abada et al., 2019). The Tunnel Optimisation Tool (TOT) was developed and used to assess the feasibility of the designs of the FCC study and their orientation with respect to the geology, terrain, surface constraints, their connection to the LHC and other siting considerations (Cook et al., 2015). TOT is focused on assessing the feasibility of FCC candidate designs from a Civil Engineering viewpoint, comparing them primarily regarding the local geology and terrain, surface constraints and connection to the LHC. The main functionalities are consolidated into a dashboard (Stanyard, Mertens, and Osborne, 2017). After two TOT versions a new tool web-application called GeoProfiler was developed. It offers more precise and integrated experience in shaft positioning and control. However, GeoProfiler does not include Evolutionary computation to automatically propose solutions, which is the goal of this work for ET.

Regarding optimisation techniques, different recent studies highlight interesting use cases. An example is environmental performance in architectural design (Wortmann, 2017), as well as broader applications in urban planning, such as land use optimisation for economic, social, and suitability objectives (Sheikh et al., 2021). Other relevant studies focus on optimising the placement of public service facilities within an urban context. The work of Turkoglu and Genevois (2020) underscores the significance of service facility placement optimisation. However, in urban planning cases, often one single placement criterion is considered. Multi criteria approaches are considered only in limited cases. In the domain of underground infrastructure, MCDM has emerged as a central approach for addressing complex design and operational challenges. Applications include optimising utility tunnel placement to balance lifecycle costs (Genger, Hammad, and Oum, 2023), predicting excavation-induced tunnel displacements (Tao et al., 2022), and refining tunnel alignments under uncertainty (Guo and Zhang, 2021). Innovations such as generative design systems for large-diameter tunnels crossing existing infrastructure demonstrate the potential of computational techniques to enhance design efficiency and precision (Lin, Zhang, and Tiong, 2023). Performance optimisation of tunnel boring machines under uncertain conditions further exemplifies the sector's advancement in adopting Multi Objective Optimisation for real-time problem-solving (Liu, Li, and Liu, 2022).

3. Method

The study commenced with the identification of key factors influencing location selection from scientific, logistical, strategic, morphological, and geological standpoints. This phase was supported by extensive consultation and discussion within both the scientific and administrative communities, thereby ensuring an interdisciplinary and methodologically robust approach to addressing the challenges associated with site optimisation. Following the definition of the relevant constraints and variables, these elements were prioritised and, where appropriate, assigned quantitative weights. In accordance with this framework, the necessary data were compiled, and a parametric model was constructed to incorporate the identified constraints. Subsequently, an optimisation solver was employed to generate a set of optimised candidate solutions.

3.1 Variables & Constraints

The variables can be divided into two groups. The first group comprises ET geometry configuration-related variables, which are independent of both placement and the hosting site and should not be optimised because it is to be defined based on the scientific community.

However, the possibility to vary the type and size of the infrastructure parametrically remains an important aspect in the parametric model for assessing the impact of the layout and comparing alternative solutions. They include the shape and length of the infrastructure and the number of emergency exits. The considered layouts are:

- Equilateral triangle with a side length of 10km
- Equilateral triangle with a side length of 15km
- L-shape with two sides of 15km length
- L-shape with two sides of the length of 20km

The second group of variables consists of placement-related metrics, which depend on the characteristics of the site and the morphology of the Earth's surface above ET. They are listed in the following Table 1.

General Constraints
Placement area domain
coordinates of the main vertex within the area domain
Scientific Requirements
Orientation of the infrastructure (Rotation)
Morphological and Topographical Characteristics
Tunnel Minimum vertical underground depth.
Cavern Minimum vertical underground depth.
Cavern Minimum earth cover (all directions)
Environmental Conditions and Administrative Constraints
Outside restricted areas
Outside national, regional parks
Outside protected and conservation areas
Vertex near existing transport infrastructure
Settling-related and Anthropogenic Interferences
Distance from Industrial Areas
Distance from Wind Farm
Distance from Town
Geological and Geotechnical Conditions
Caverns to be placed outside weak geologic material
Caverns to be placed in specific geologic material

Table 1 List of placement-related metrics variables.

3.2 Scoring And Weighting

The criteria mentioned earlier can be classified into two evaluation categories for the optimisation process:

- **Binary Solutions:** Based on Boolean exclusion, where solutions outside a specific domain are automatically excluded. For example, placements within protected national park regions could be entirely disallowed.
- **Maximising or Minimising Distances:** This involves optimising criteria such as maximising the distance from wind farms and minimising the volume of terrain that must be excavated.

While binary criteria, such as avoiding restricted zones, are straightforward, definitive, and require no further refinement, the second category introduces numerous possibilities for optimisation. For instance, increasing the distance from noise sources would enhance the quality of the interferometer (the farther, the better), whereas reducing the distance from existing urban infrastructure would reduce some costs (the closer, the better). Therefore, the effect of maximising or minimising certain values could improve the solution of a specific criterion in a linear or logarithmic way. However, improving one criterion may conflict with others. This means that many involved criteria may be directly or indirectly in conflict, making it challenging to determine an optimal solution. This necessitates a weighting system to establish the relative importance of each criterion, allowing the optimisation algorithm to navigate trade-offs and prioritise objectives according to the project's strategic goals and focus on achieving the most meaningful trade-offs.

To prevent criteria with larger numerical ranges from dominating the optimisation process, all variables are normalised to a standard, dimensionless scale before weighting. Specifically, each criterion's value is re-mapped (e.g., to a 0–1 range) to eliminate discrepancies in units and magnitudes. This ensures that every criterion contributes proportionally to the aggregated fitness function, resulting in a balanced and representative optimisation outcome that reflects the decision-makers' priorities. Consequently, an approximate priority weight parameter (from 1 to 10) was assigned to every criterion when applicable.

The specific values assigned to these weights, at this phase of the project, should be considered as a first approximation, derived from preliminary surveys and consultations with the various scientific working groups involved in the ET project. Based on this consensus, criteria directly impacting the core scientific mission, such as isolation from seismic, thermal, and anthropogenic noise, were assigned higher priority weights. Conversely, criteria related to logistical convenience or infrastructural costs were assigned lower weights. However, these specific values are indicative, as the objective of this study is to validate the proposed computational workflow rather than to establish final design parameters. Because the developed framework is entirely parametric, the weighting system acts as a flexible interface. As the project advances, these weights can be seamlessly adjusted to generate new optimisation scenarios without requiring alterations to the underlying algorithm.

3.3 Data and Processing

For this analysis, three categories of data were generated or collected:

Parametric model – encompassing aspects related to geometry and accessibility, such as overall shape and emergency exits. At this stage, the model should remain highly abstract.

Context model – representing the terrain through a Digital Terrain Model (DTM) of the study area, with a spatial resolution appropriate to the required level of precision.

GIS data – including layers such as urban areas, road networks, and the locations of wind turbines.

Initially, the 3D models and GIS datasets must be aligned within a common reference system to ensure proper spatial correspondence. Subsequently, 2D GIS data should be converted to 3D where necessary. For instance, the locations of wind turbines, typically provided as 2D vector data, can be projected onto the Digital Terrain Model (DTM) surface using associated metadata to enable more accurate spatial calculations.

The ET infrastructure model is then related to the terrain through two key operations:

Computation of distances between the ET infrastructure and relevant environmental or anthropogenic features (Figure 2).

Calculation of depth profiles along the tunnel and projection of access point locations onto the DTM.

As these operations are fully parameterised within a computational framework, the tool provides instantaneous analytical feedback in response to modifications of the input positioning parameters. Specifically, it is capable of automatically determining the minimum and maximum underground depths along the tunnel for a given configuration, quantifying the minimum distances to specific categories of objects, and evaluating the maximum separation from existing supporting infrastructure.

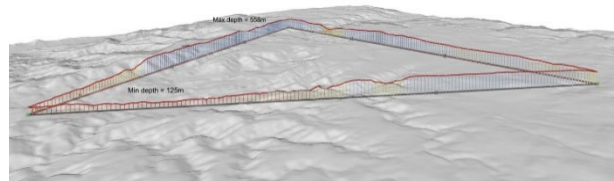


Figure 2 Conceptual layout of the ET Triangle interferometer.

The tunnel axes are shown by the black line, and its projection onto the Digital Terrain Model (DTM) is shown by the red line.

An additional critical aspect of the project concerns the design and placement of the main entrances to the underground infrastructure. A particularly promising alternative, where geological and spatial conditions permit, is the implementation of horizontal access through a ramp tunnel rather than a conventional vertical shaft. This configuration can substantially enhance logistical efficiency by facilitating the transport of technical components, vehicles, and personnel into the underground facility. By integrating the Digital Terrain Model (DTM) with the parametric ET model, this aspect can be systematically evaluated through the introduction of a criterion that constrains the maximum allowable inclination of an access tunnel. This criterion enables the generation of potential entrance points at the vertices of the two possible configuration geometries, allowing for the identification of the shortest viable access paths based on the projection of these vertex points onto the DTM (Figure 3).

Up to this stage, the parametric model supports the systematic adaptation of the infrastructure's position in accordance with varying conditions and input parameters, providing real-time feedback on alternative configuration states. However, the transition to automated optimisation necessitates the formulation of a suitable fitness function and the deployment of evolutionary computation techniques.

3.4 Variables & optimising criteria

The criteria and optimisation parameters incorporated into this study, along with their corresponding constraints used to delimit the search space, are summarised in Table 2. Where appropriate, weighting factors were assigned to indicate the relative importance of individual criteria within the overall optimisation process. In this work, we adopt a scalarisation approach for the optimisation problem rather than using standard multi-objective optimisation algorithm, such as NSGA-II, which are typically employed to generate a Pareto front of non-dominated solutions. Specifically, the multiple criteria are transformed into a single scalar objective through a fitness function that computes the sum of all normalised then weighted criterion values. This enables the use of single-objective evolutionary solvers, such as Galapagos. This approach also provides good control over the fitness function and the weighting scheme, allowing the resulting solutions to be aligned with the project’s strategic priorities.

4. Solution

The geometric and positional variables used for ET, along with the corresponding input parameters and constraints considered for its placement, are summarised below:

- ET geometry configurations: Triangle (10 km, 15 km) and L-shape (15 km, 20 km)
- Search domain: Area defined by E, W, N & S coordinates.
- Vertex 1 position: X_{v1} and Y_{v1} , as percentages of the domain's width and height
- Elevation: Z_{v1} , height of vertex 1 above sea level
- Rotation: Orientation of the infrastructure around vertex 1

4.1 Input data

The primary data types used in the analysis include 3D models, 2D GIS layers, and a set of parametric inputs. The input dataset consists of GIS data, providing spatial and morphological information for the predefined area where the infrastructure is to be placed. A key component is the DTM, represented as a mesh. In the tested dataset, a tessellation of 40 meters was applied over a 32×32 km area. This was obtained by the resampling of the 10-meter DTM sourced from the SardegnaSit GIS portal, which is managed by the Sardinia Region.

The DTM, like other input data, could be replaced with other data, including data with higher or lower resolutions, but this could affect computation times.

This dataset, which covers the entire regional territory, was created from the 'contour lines' and 'spot heights' layers of the 1:10,000 Geotopographic Database (DBGT 10K).

Additional GIS layers include municipal boundaries, existing buildings, the road network (urban and suburban), restricted zones, and industrial areas. These were also obtained from the Sardinia Region's Geoportal. Populated areas were identified through a clustering process that aggregates buildings based on configurable parameters—for example, groups consisting of at least 50 buildings with inter-building distances of less than 150 meters. These parameters are user-defined and can be adjusted to refine the analysis.

The dataset also includes the 2D coordinates and installed power capacities (in kilowatts) of wind turbines located in the areas of Bitti, Buddusò, Nule, and Onani, in Excel format. This data was obtained by the constant monitoring of projects on the official website of the Italian Ministry of the Environment and Energy Security (Ministero dell’Ambiente e della Sicurezza Energetica, 2025).

4.2 Analysis and visualisations

The following analyses are implemented:

Depth analysis: The tool evaluates the vertical positioning of the infrastructure relative to the ground surface. It identifies the points where the cover (depth) is minimum and maximum, displaying this information through a colour gradient. These two extremes are annotated with precise textual information specifying their location and the relative distance between them.

Distance to road network: The software computes the minimum horizontal linear distance between each infrastructure vertex and the road network, including both urban and suburban roads. It identifies and displays the nearest road segments and highlights the closest feasible connection points. These distances are shown directly in the graphical viewer (Viewport).

Distance to populated areas: This analysis estimates the shortest horizontal linear distance between ET vertices and nearby populated areas. The analysis helps estimate proximity to urban zones, with distances again visualised in the viewer for quick interpretation.

Criteria & optimising parameters						
ID	Criteria	Aim	Optimisation	Constraints		Weight
				min	max	
1 Search limits						
1,1	Vertex V1 location X (East west)	Exclude solutions outside the constraint domain (specific area)	n/a	E. Co.	W. Co.	n/a
1,2	Vertex V1 location Y (North south)	Exclude solutions outside the constraint domain (specific area)	n/a	S. Co.	N. Co.	n/a
1,3	Vertex V1 Altitude	Exclude solutions outside the constraint domain (Elevation above sea level)	n/a	100	800	n/a
1,4	Rotation (V1 as base point)	Exclude solutions outside the constraint domain (Angle relative to north)	n/a	N(-45°)	N(+45°)	n/a
2 Morphological and Topographical Characteristics						
2,1	Tunnel earth cover (Vertical)	Minimising the cover for the closest part of the tunnel to earth surface	Minimise	40 M	n/a	7
2,2	Cavern earth cover (Vertical)	Minimising the cover for the closest vertex to earth surface	Minimise	120 M	n/a	10
2,3	Cavern earth cover overall (Vertical)	Minimising the sum of vertical cover of the 3 Vertices	Minimise	n/a	n/a	10
3 Environmental Conditions and Administrative Constraints						
3,1	Restricted areas	No 2D intersection with ET geometry	Avoid zone	n/a	n/a	n/a
3,2	Existing roads	Close to ET vertices (The closer, the better)	Minimise	n/a	n/a	5
3,3	Viaducts	Far from ET Vertices (Outside the specified range & The farther away, the better)	Maximise	3 KM	n/a	10
4 Settling-related and Anthropogenic Interferences						
4,1	Industrial Area "Nuoro"	Far from ET Vertices (Outside the specified range)	Avoid zone	15 KM	n/a	10
4,2	Wind turbines "Buddusò"	Far from ET Vertices (The farther away, the better)	Maximise	15 KM	n/a	10
4,3	Towns / populated zones	Close to ET vertices (The closer, the better)	Minimise	n/a	n/a	2
4,4	Industrial Area "Sologo"	Far from ET Vertices (Outside the specified range)	Avoid zone	15 KM	n/a	7

Table 2 Criteria and optimisation parameters example of application for the Sardinia region

Proposed placement

Metrics

Linear dist. to closest Wind turbine	14729
Linear dist. to closest viaduct	4827
Sum of linear dist. to Vertices closest urban areas	10759
Minimum depth of a vertex	140
Minimum depth from the terrain surface along the tunnel	41
Maximum depth from the terrain surface along the tunnel	593
Intersection with restricted areas?	False
Tunnel within 15km to Nuoro industrial zone?	False
Sum of the depth for all vertices	1105

Representation

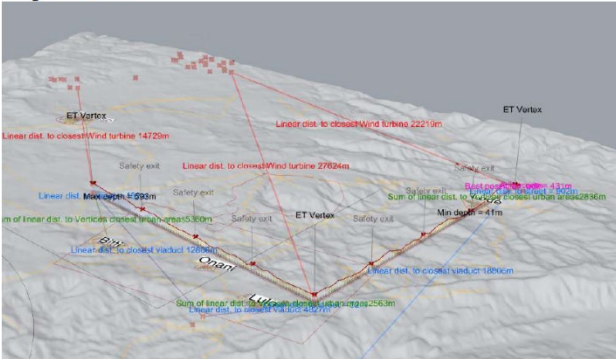


Figure 5 Example of an output configuration and its associated parameters, based on one of the input parameter variations for the Sardinia site¹.

6. Conclusion

This study demonstrates the value of integrating GIS with parametric modelling as a coherent framework for supporting placement optimisation and spatial decision-making in complex infrastructural projects. The combination of these approaches enabled the systematic exploration of spatial constraints, the dynamic adaptation of design parameters, and the clear visualisation of alternative configuration scenarios. Building upon this foundation, the incorporation of evolutionary algorithm further strengthened the analytical capacity of the workflow, allowing the system not only to propose new solutions as parameters evolve throughout the design process but also to robustly evaluate alternative proposals originating from different stakeholders.

A key strength of the proposed methodology is its degree of generalizability. Because the framework relies on parametric modelling and standardised GIS data formats, it is not strictly bound to the local morphology of the case study. The system can be readily applied to the other competing candidate sites, such as the Euregio Meuse-Rhine or the Lusatia Region. Adapting the tool to a new location simply requires updating the input datasets, namely, replacing the local DTM and the relevant 2D/3D GIS layers (e.g., infrastructure networks, restricted areas), and redefining the boundary domain. The core computational logic and optimization algorithms remain entirely valid and functional without requiring structural changes to the code.

Such an optimisation-driven methodology has the potential to enhance the overall quality of the placement while also identifying cost-efficient configurations that may significantly influence project feasibility. Collectively, these contributions highlight the relevance of computational and data-driven methods in supporting transparent, efficient, and adaptable decision-making within contemporary infrastructure planning.

7. Outlook

Future developments of this research will focus on expanding the analytical scope of the proposed framework through the integration of detailed geological information and subsurface modelling. Incorporating multi-site assessments, geological stratigraphy, and geohazard analyses will enable a more comprehensive evaluation of risks and constraints associated with each potential location. Furthermore, the parametric model can be enriched with higher levels of geometric and informational detail, ultimately evolving toward BIM-GIS Integration environment. While the creation of a Digital Twin remains a long-term ambition, the incremental enrichment of the model will lay the foundational elements required for such an advanced representation. By integrating these additional layers of analysis and validation, the framework will become increasingly robust, offering improved predictive capabilities and strengthening the reliability of decision-making processes across subsequent project phases.

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References

- Abada, A., M. Abbrescia, S. S. AbdusSalam, I. Abdyukhanov, J. Abelleira Fernandez, A. Abramov, M. Aburaia, et al., 2019. 'FCC-Hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3'. *The European Physical Journal Special Topics* 228(4): 755–1107. doi:10.1140/epjst/e2019-900087-0.
- Abbott, B. P., R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, et al., 2016. 'Observation of Gravitational Waves from a Binary Black Hole Merger'. *Physical Review Letters* 116(6): 061102. doi:10.1103/PhysRevLett.116.061102.
- Abbott, R., H. Abe, F. Acernese, K. Ackley, N. Adhikari, R. X. Adhikari, V. K. Adkins, et al., 2023. 'Constraints on the Cosmic Expansion History from GWTC-3'. *The Astrophysical Journal* 949(2): 76. doi:10.3847/1538-4357/ac74bb.
- Amann, F., Bonsignorio, F., Bulik, T., Jan Bulten, H., Cuccuru, S., Dassargues, A., DeSalvo, R., et al., 2020. 'Site-Selection Criteria for the Einstein Telescope'. *Review of Scientific Instruments* 91(9): 094504. doi:10.1063/5.0018414.
- Back, T., U. Hammel, and H.-P. Schwefel., 1997. 'Evolutionary Computation: Comments on the History and Current State'. *IEEE Transactions on Evolutionary Computation* 1(1): 3–17. doi:10.1109/4235.585888.
- Branchesi, M., Maggiore, M., Alonso, D., Badger, Ch., Banerjee, B., Beirnaert, F., Belgacem, E., et al., 2023. 'Science with the Einstein Telescope: A Comparison of Different Designs'. *Journal of Cosmology and Astroparticle Physics* 2023(07): 068. doi:10.1088/1475-7516/2023/07/068.
- Buikema, A., 2020. 'Sensitivity and Performance of the Advanced LIGO Detectors in the Third Observing Run'. *Physical Review D* 102(6). doi:10.1103/PhysRevD.102.062003.

- Coello Coello, C.A., Lamont, G.B., Van Veldhuizen, D.A., 2007. *Evolutionary Algorithms for Solving Multi-Objective Problems* Second Edition. 2nd edn Springer Science+Business Media.
- Cook, C., Goddard, B., Lebrun, Ph., Osborne, J., and Robert, Y., 2015. 'Civil Engineering Optimisation Tool for the Study of CERN's Future Circular Colliders'. *Proceedings of the 6th Int. Particle Accelerator Conf. IPAC2015*: 3 pages, 0.543 MB. doi:10.18429/JACOW-IPAC2015-TUPTY033.
- ESFRI, 2021. 'Strategy Report on Research Infrastructures - Part 2'. <https://roadmap2021.esfri.eu/>.
- Fischer, M., Ashcraft, H., Reed, D., Khanzode, A., 2017. *Integrating Project Delivery*. Hoboken, New Jersey: Wiley. doi:10.1002/9781119179009.
- Genger, K.T., Hammad, A., Oum, N., 2023. 'Multi-Objective Optimization for Selecting Potential Locations of Multi-Purpose Utility Tunnels Considering Agency and Social Lifecycle Costs'. *Tunnelling and Underground Space Technology* 140: 105305. doi:10.1016/j.tust.2023.105305.
- Guo, K., Zhang, L., 2021. 'Multi-Objective Optimization in Tunnel Line Alignment under Uncertainty'. *Automation in Construction* 122: 103504. doi:10.1016/j.autcon.2020.103504.
- Hild, S., M. Abernathy, F. Acernese, P. Amaro-Seoane, N. Andersson, K. Arun, F. Barone, et al. 2011. 'Sensitivity Studies for Third-Generation Gravitational Wave Observatories'. *Classical and Quantum Gravity* 28(9): 094013. doi:10.1088/0264-9381/28/9/094013.
- Khamis, A., 2024. *Optimization Algorithms: AI Techniques for Design, Planning, and Control Problems*. 1st ed. New York: Manning Publications Co. LLC.
- Koley, S., Bader, M., Van Den Brand, J., Campman, X., Jan Bulten, H., Linde, F., Vink, B., 2022. 'Surface and Underground Seismic Characterization at Terziet in Limburg—the Euregio Meuse–Rhine Candidate Site for Einstein Telescope'. *Classical and Quantum Gravity* 39(2): 025008. doi:10.1088/1361-6382/ac2b08.
- Lin, P., Zhang, L., Tiong, R.L.K., 2023. 'Multi-Objective Optimization Ensembled Generative Design for Large-Diameter Tunnel Passing underneath Existing Tunnels'. *Applied Soft Computing* 144: 110448. doi:10.1016/j.asoc.2023.110448.
- Liu, W., Li, A., Liu, C., 2022. 'Multi-Objective Optimization Control for Tunnel Boring Machine Performance Improvement under Uncertainty'. *Automation in Construction* 139: 104310. doi:10.1016/j.autcon.2022.104310.
- Ministero dell'Ambiente e della Sicurezza Energetica. 2025. 'Valutazioni e Autorizzazioni Ambientali: VAS - VIA - AIA'. <https://va.mite.gov.it/it-IT> (November 14, 2025).
- Muccini, F., Greco, F., Cocchi, L., Marsella, M., Zanutta, A., Borghi, A., Cagnizi, M., et al. 2025. 'Airborne Strapdown Gravity Survey of Sos Enattos Area (NE Sardinia, Italy): Insights into Geological and Geophysical Characterization of the Italian Candidate Site for the Einstein Telescope'. *Remote Sensing* 17(13): 2309. doi:10.3390/rs17132309.
- Muthumanickam, N.K., Brown, N., Duarte, J.P., Simpson, T.W., 2023. 'Multidisciplinary Design Optimization in Architecture, Engineering, and Construction: A Detailed Review and Call for Collaboration'. *Structural and Multidisciplinary Optimization* 66(11): 239. doi:10.1007/s00158-023-03673-y.
- Naticchioni, L., Boschi, V., Calloni, E., Capello, M., Cardini, A., Carpinelli, M., Cuccuru, S., et al., 2020. 'Characterization of the Sos Enattos Site for the Einstein Telescope'. *Journal of Physics: Conference Series* 1468(1): 012242. doi:10.1088/1742-6596/1468/1/012242.
- Rutten, D., 2013. 'Galapagos: On the Logic and Limitations of Generic Solvers'. *Architectural Design* 83(2): 132–35. doi:10.1002/ad.1568.
- Sathyaprakash, B., Abernathy, M., Acernese, F., Ajith, P., Allen, B., Amaro-Seoane, P., Andersson, N., et al., 2012. 'Scientific Objectives of Einstein Telescope'. *Classical and Quantum Gravity* 29(12): 124013. doi:10.1088/0264-9381/29/12/124013.
- Sheikh, V., Salmani, H., Mahiny, A.S., Ownegh, M., Fathabadi, A., 2021. 'Land Use Optimization through Bridging Multiobjective Optimization and Multicriteria Decision-making Models (Case Study: Tilabad Watershed, Golestan Province, Iran)'. *Natural Resource Modeling* 34(2). doi:10.1111/nrm.12301.
- Stanyard, J., Mertens, V., Osborne, J., Loo, Y., Sturzaker, C., Sykes, M., 2017. 'Optimisation of the Design of the Future Circular Collider from a Civil Engineering Perspective'. Tao, Yuanqin, Wei He, Honglei Sun, Yuanqiang Cai, and Junqiang Chen. 2022. 'Multi-Objective Optimization-Based Prediction of Excavation-Induced Tunnel Displacement'. *Underground Space* 7(5): 735–47. doi:10.1016/j.undsp.2021.12.005.
- Turkoglu, C.D., Genevois, M.E., 2020. 'A Comparative Survey of Service Facility Location Problems'. *Annals of Operations Research* 292(1): 399–468. doi:10.1007/s10479-019-03385-x.
- Villani, F., Maraio, S., Improta, L., De Martini, P.M., Cavallaro, D., Firetto Carlino, M., Brunori, C.A., et al. 2024. 'Subsurface Characterization of Crystalline Rocks at the Einstein Telescope Candidate Site (Italy): Insights from Seismic Tomography, Geoelectrical and Morphostructural Surveys'. doi:10.2139/ssrn.5063240.
- Wortmann, Th., 2017. 'Model-Based Optimization for Architectural Design: Optimizing Daylight and Glare in Grasshopper'. *Technology|Architecture + Design* 1(2): 176–85. doi:10.1080/24751448.2017.1354615.
- Yavan, F., Maalek, R., Toğan, V., 2024. 'Structural Optimization in Building Information Modeling (BIM) Projects Using Visual Programming, Evolutionary Algorithms, and Sustainability Assessment Tools'. doi:10.20944/preprints202404.0060.v1.

ⁱ Please note that ET configuration and placements proposals presented in this article is solely for illustrative purposes and may not represent real study data.