University of Applied Sciences and Arts Northwestern Switzerland
School of Architecture, Construction and Geomatics

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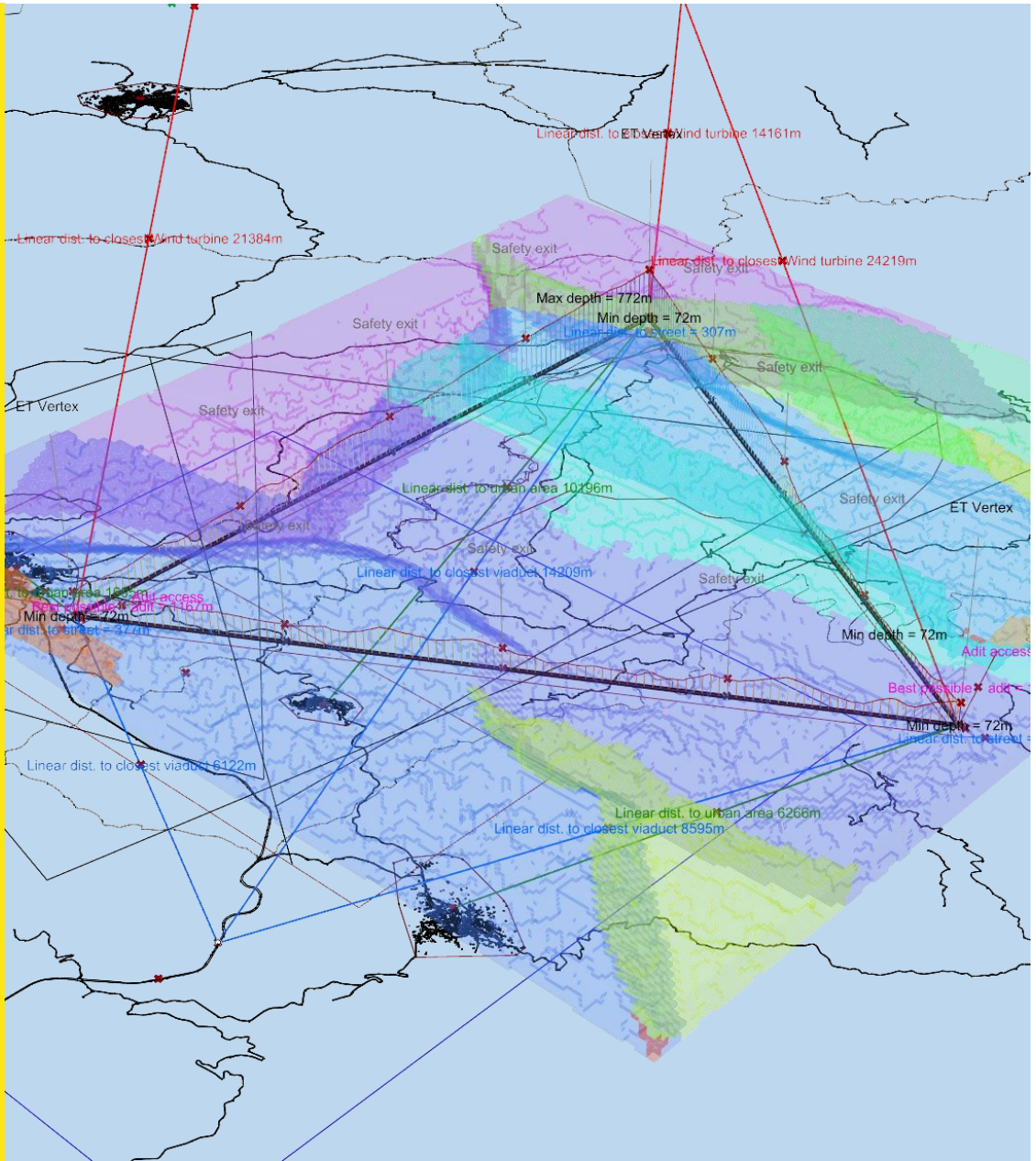
Digital Modeling and Data-Driven approach for infrastructure design

Einstein Telescope Research Infrastructure: Challenges and Long-Term Sustainability



Wissam, Wahbeh

16/02/2026

What “Data-Driven Optimisation” Means in Construction

A data-driven methodology uses **measured, simulated, and historical data** to:

- Define objective functions (cost, carbon, risk, resilience, energy use)
- Quantify constraints (geology, regulations, land use, capacity)
- Evaluate multiple design scenarios
- Select optimal solutions based on measurable criteria

Rather than optimizing only for cost, modern infrastructure optimization integrates:

- Economic performance
- Environmental impact (CO_2, material use, water impact)
- Social and operational resilience

Types of Data Used in Construction

Design & Planning Data

- GIS layers (topography, land use, environmental constraints)
- Geological and geotechnical models
- Hydrological and climate datasets

Construction Data

- Productivity rates
- Equipment performance
- Material quantities
- Energy consumption

Monitoring & Operational Data

- Sensor data (IoT)
- Structural health monitoring
- Traffic flow / usage patterns
- Maintenance records

Environmental Data

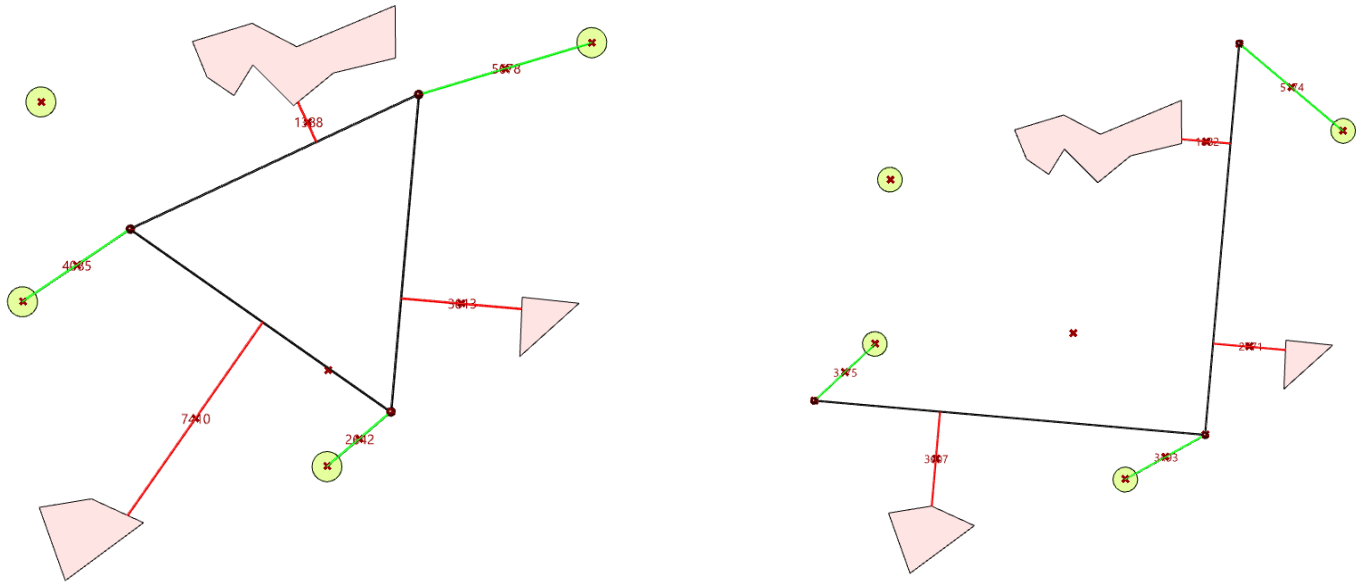
- Embodied carbon databases
- Life Cycle Assessment (LCA) datasets
- Water table monitoring
- Emission measurements

Methodological Approaches

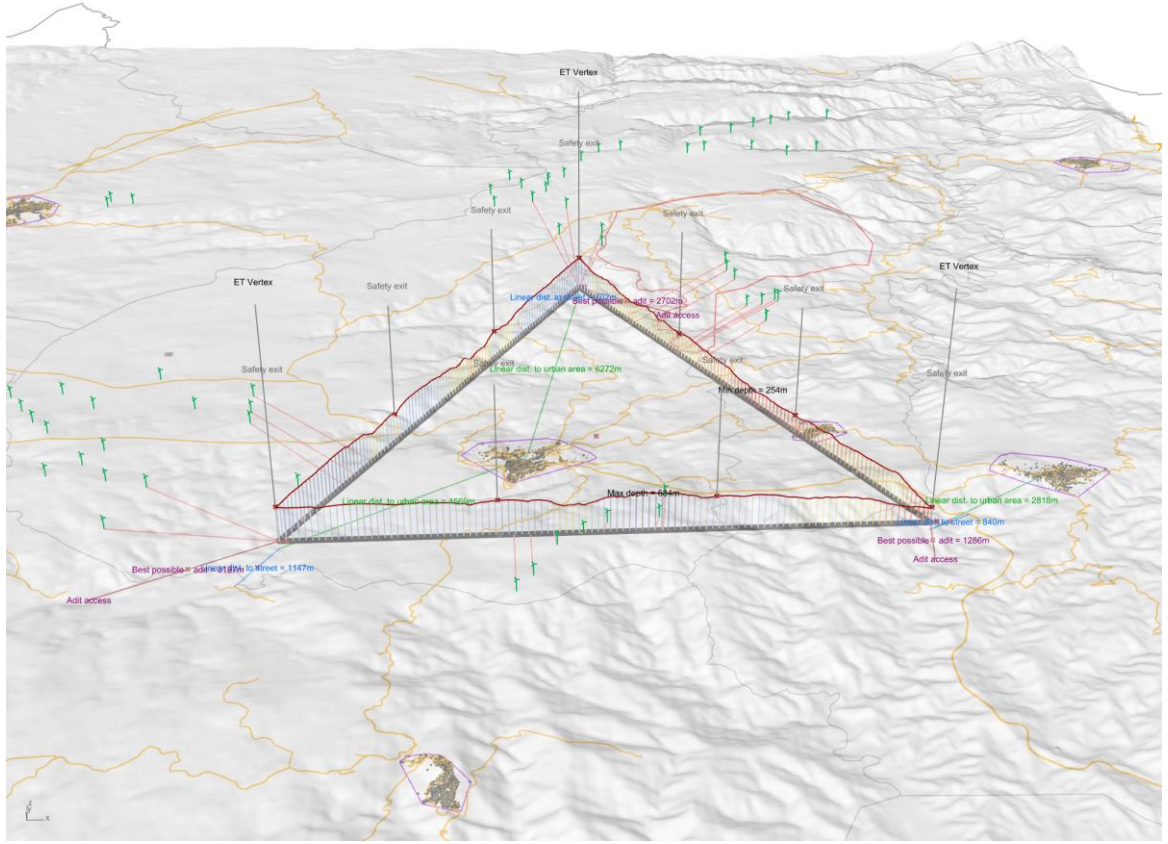
- Parametric & Algorithmic Optimization
- Probabilistic & Risk-Based Models
- BIM–GIS Integration
- Multi-Criteria Decision Analysis (MCDA)
- Digital Twins

Parametric approach

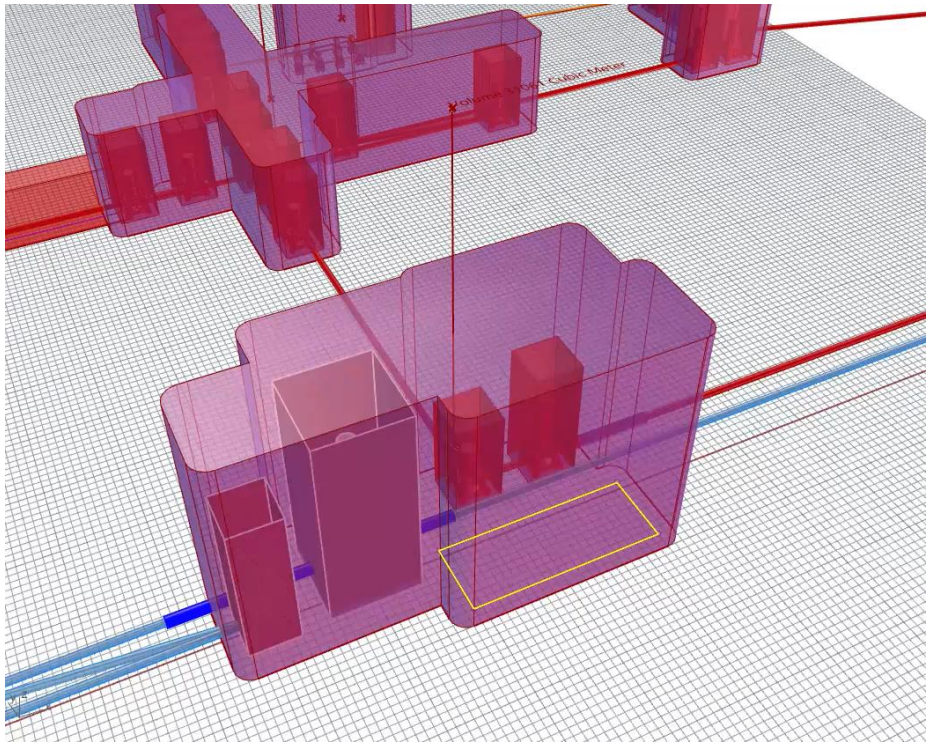
Parametric modelling and muti objective optimisation approach were used in ET in a tool for preliminary assessments of placement situations and then to estimate costs interactively based on quantitative calculations during the experimentation of layout variables.



Parametric approach

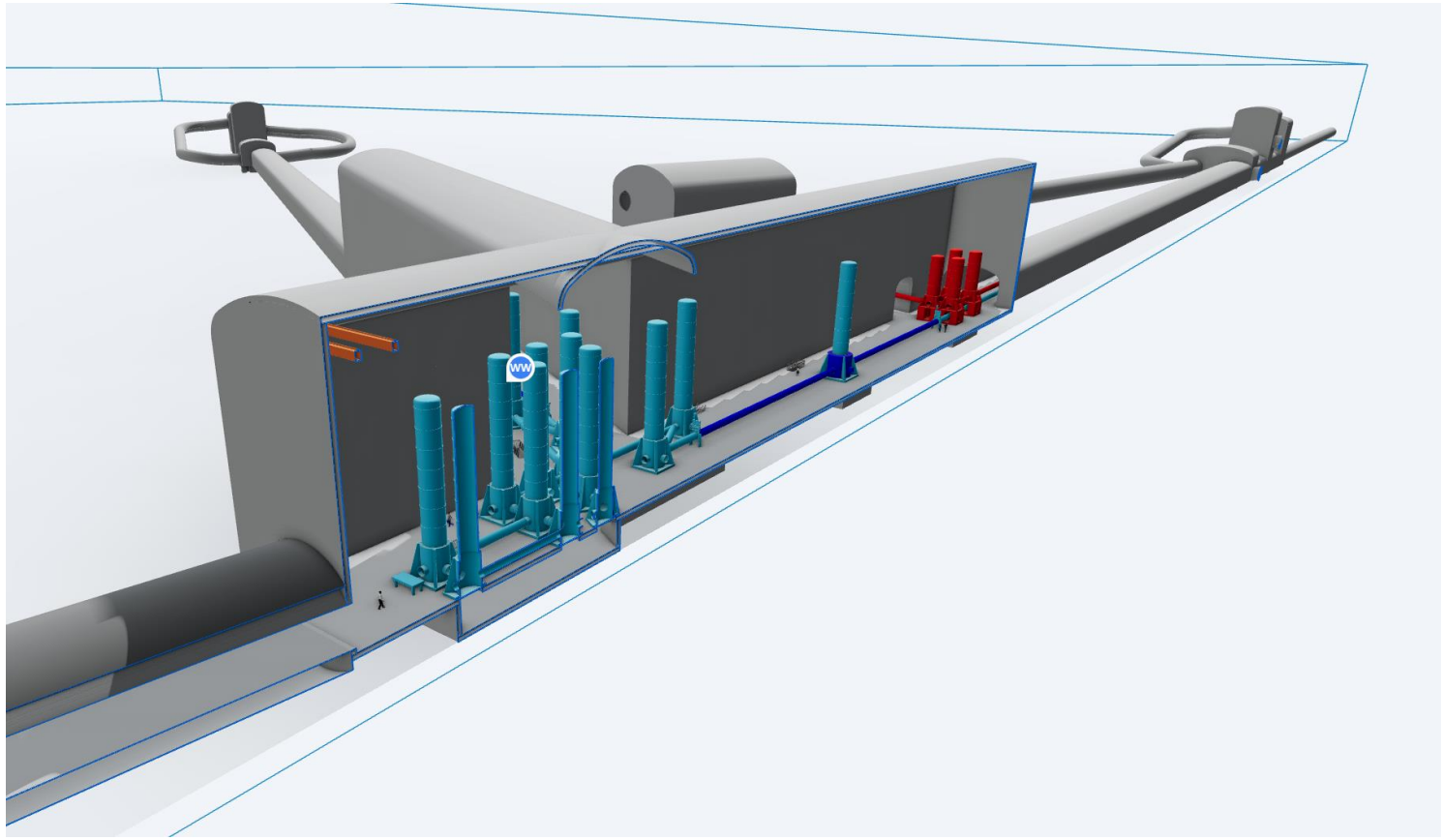


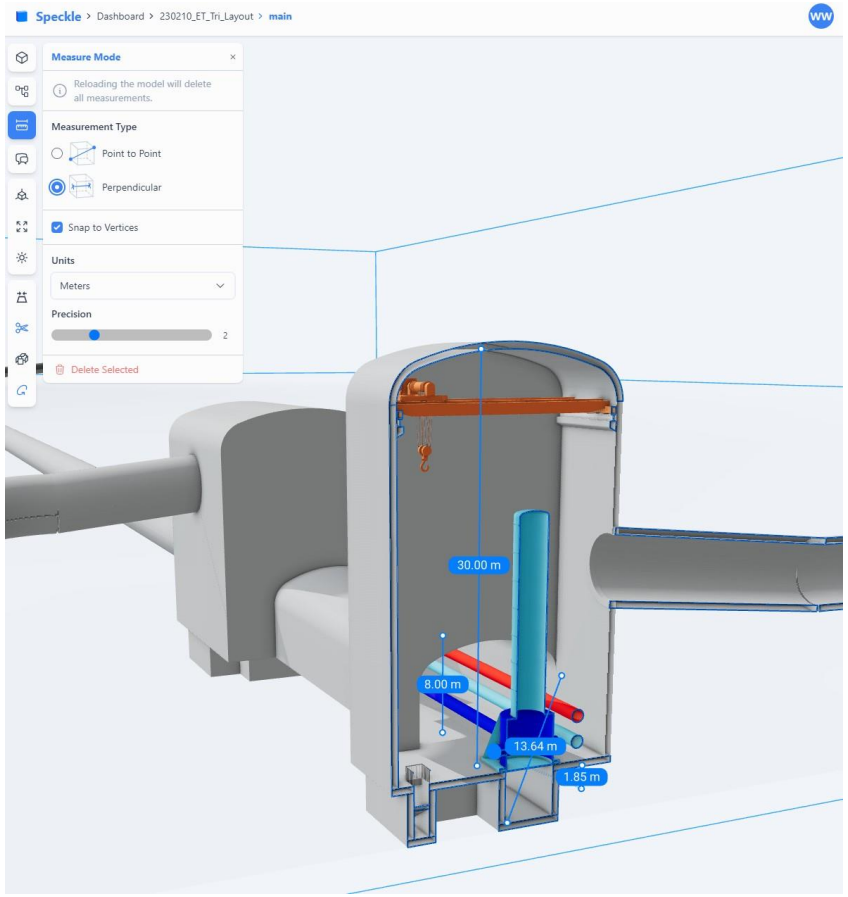
assessments of placement situations



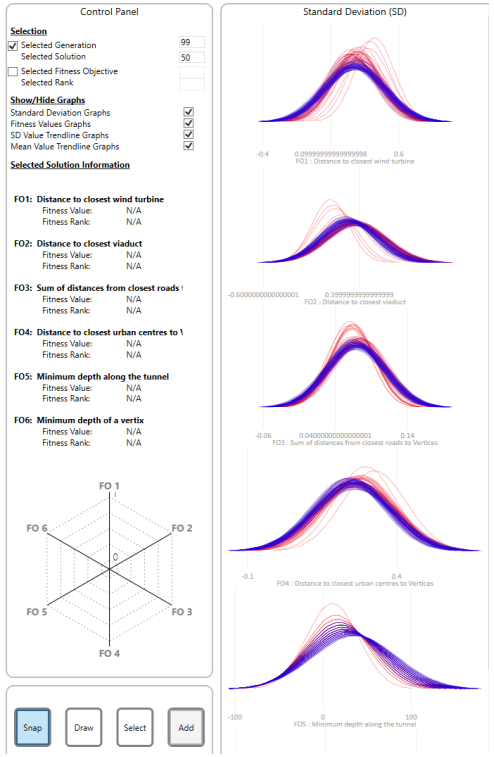
Estimating quantiites and costs based during the experimentation of layout variables.

BIM Models

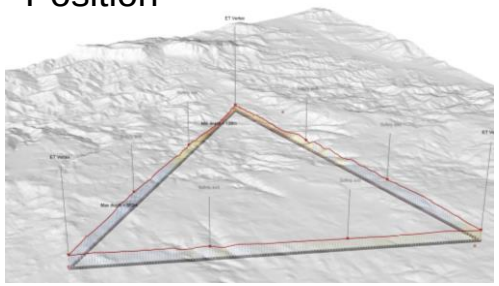



Speckle > Dashboard > 230210_ET_Tri_Layout > main
Measure Mode
Reloading the model will delete all measurements.
Measurement Type
Point to Point
Perpendicular
Snap to Vertices
Units
Meters
Precision
2
Delete Selected
30.00 m
8.00 m
13.64 m
1.85 m

ID	Criteria	Aim	Optimisation	min	max	Weight
1	search limits					
1.1	Vertex V1 location X (East west)	Vertix 1 inside granit area				
1.2	Vertex V1 location Y (North south)	Vertix 1 inside granit area				
1.3	Vertex V1 Altitude					
1.4	Rotation (V1 as base point)			0°	360°	
2	SCIENTIFIC REQUIREMENTS					
2.1	No scientific requirments					
3	MORPHOLOGICAL AND TOPOGRAPHICAL CHARACTERISTICS					
3.1	Tunnel earth cover (Vertical direction)	Minimising the cover for the closest part of the tunnel to earth surface	Minimise dis.	40 M		7
3.2	Cavern earth cover (Vertical direction)	Minimising the cover for the closest vertix to earth surface	Minimise dis.	120 M		10
3.3	Cavern earth cover overall (Vertical direction)	Minimising the sum of vertical cover of the 3 Vertices	Minimise dis.			10
4	ENVIROMENTAL AND ADMINISTRATIVE COSTRAINTS					
4.1	Restricted areas	No 2D intersection	Avoid zone			
4.2	Existing roads	Close to the vertices	Minimise dis.			5
4.3	Viadotti	Min distance 3 km from vertices, try "The farer the better"	Maximise dis.			10
5	INSEDIATIVE AND ANTHOPIC INTERFERENCES					
5.1	Industrial Area Nuoro	Far from the Vetices (Out of GIS Radius)	Avoid zone	15 KM		10
5.2	Wind turbines Budduso'	Far from the Vetices	Maximise dis.	15 KM		10
5.3	Towns / populated zones	Close to the vertices	Minimise dis.			2
5.4	Industrial Area Sologo	Far from the Vetices	Maximise dis.			7
6	Geological Criteria					
6.1	Vertix 1 inside granit area					



Position



Parametric approach, Multi-criterial analysis

Criteria & optimising parameters

ID	Criteria	Aim	Optimisation	Constraints min	Constraints max	Weight
1	search limits					
1.1	Vertex V1 location X (East west)	Vertix 1 inside granit area		Bitti -1000	Bitti +8000	
1.2	Vertex V1 location Y (North south)	Vertix 1 inside granit area		Bitti -1000	Bitti +2000	
1.3	Vertex V1 Altitude			200	800	
1.4	Rotation (V1 as base point)			N(-10°)	N(+45°)	
2	SCIENTIFIC REQUIREMENTS					
2.1	No scientific requirments					
3	MORPHOLOGICAL AND TOPOGRAPHICAL CHARACTERISTICS					
3.1	Tunnel earth cover (Vertical)	Minimising the cover for the closest part of the tunnel to earth surface	Minimise dis.	40 M		7
3.2	Cavern earth cover (Vertical)	Minimising the cover for the closest vertix to earth surface	Minimise dis.	120 M		10
3.3	Cavern earth cover overall (Vertical)	Minimising the sum of vertical cover of the 3 Vertices	Minimise dis.			10
4	ENVIROMENTAL AND ADMINISTRATIVE COSTRAINTS					
4.1	Restricted areas	No 2D intersection	Avoid zone			
4.2	Existing roads	Close to the **vertices**	Minimise dis.			5
4.3	Viaducts	Min distance 3 km from vertices, try "The farer the better"	Maximise dis.	3		10
5	INSEDIATIVE AND ANTHOPIC INTERFERENCES					
5.1	Industrial Area Nuoro	Far from the **Vetices** (Out of GIS Radius)	Avoid zone	15 KM		10
5.2	Wind turbines Budduso'	Far from the **Vetices**	Maximise dis.	15 KM		10
5.3	Towns / populated zones	Close to the **vertices**	Minimise dis.			2
5.4	Industrial Area Sologo	Far from the **Vetices**	Maximise dis.			7
6	Geological Criteria					
6.1	Vertix 1 inside granit area					

Results

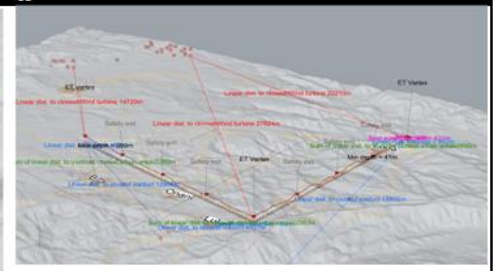
Metrics	Location 2D	Location 3D
Linear dist. to closest Wind turbine	10235	
Linear dist. to closest viaduct	7558	
Sum of linear dist. to Vertices closest urban areas	14145	
Minimum depth of a vertix	141	
Minimum depth from the terrain surface along the tunnel	45	
Maximum depth from the terrain surface along the tunnel	504	
Intersection with restricted areas?	False	
Tunnel within 15km to Nuoro industrial zone?	False	
Sum of the depth for all vertices	448	

Criteria & optimising parameters

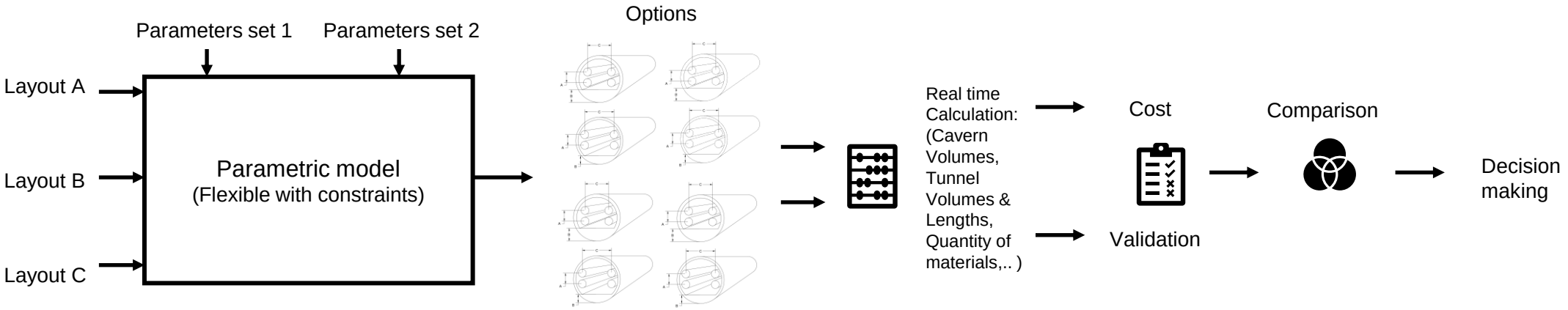
ID	Criteria	Aim	Optimisation	Constraints min	Constraints max	Weight
1	search limits					
1.1	Vertex V1 location X (East west)	Vertix 1 inside granit area		Bitti -1000	Bitti + 12000	
1.2	Vertex V1 location Y (North south)	Vertix 1 inside granit area		Bitti -2000	Bitti + 5000	
1.3	Vertex V1 Altitude			100	800	
1.4	Rotation (V1 as base point)			N(-45°)	N(+45°)	
2	SCIENTIFIC REQUIREMENTS					
2.1	No scientific requirments					
3	MORPHOLOGICAL AND TOPOGRAPHICAL CHARACTERISTICS					
3.1	Tunnel earth cover (Vertical)	Minimising the cover for the closest part of the tunnel to earth surface	Minimise dis.	40 M		7
3.2	Cavern earth cover (Vertical)	Minimising the cover for the closest vertix to earth surface	Minimise dis.	120 M		10
3.3	Cavern earth cover overall (Vertical)	Minimising the sum of vertical cover of the 3 Vertices	Minimise dis.			10
4	ENVIROMENTAL AND ADMINISTRATIVE COSTRAINTS					
4.1	Restricted areas	No 2D intersection	Avoid zone			
4.2	Existing roads	Close to the **vertices**	Minimise dis.			5
4.3	Viaducts	Min distance 3 km from vertices, try "The farer the better"	Maximise dis.			10
5	INSEDIATIVE AND ANTHOPIC INTERFERENCES					
5.1	Industrial Area Nuoro	Far from the **Vetices** (Out of GIS Radius)	Avoid zone	15 KM		10
5.2	Wind turbines Budduso'	Far from the **Vetices**	Maximise dis.	15 KM		10
5.3	Towns / populated zones	Close to the **vertices**	Minimise dis.			2
5.4	Industrial Area Sologo	Far from the **Vetices**	Maximise dis.			7
6	Geological Criteria					
6.1	Vertix 1 inside granit area					

Results

Metrics	Location 2D	Location 3D
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 vertix	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	
V1 Out of Granit geological area		

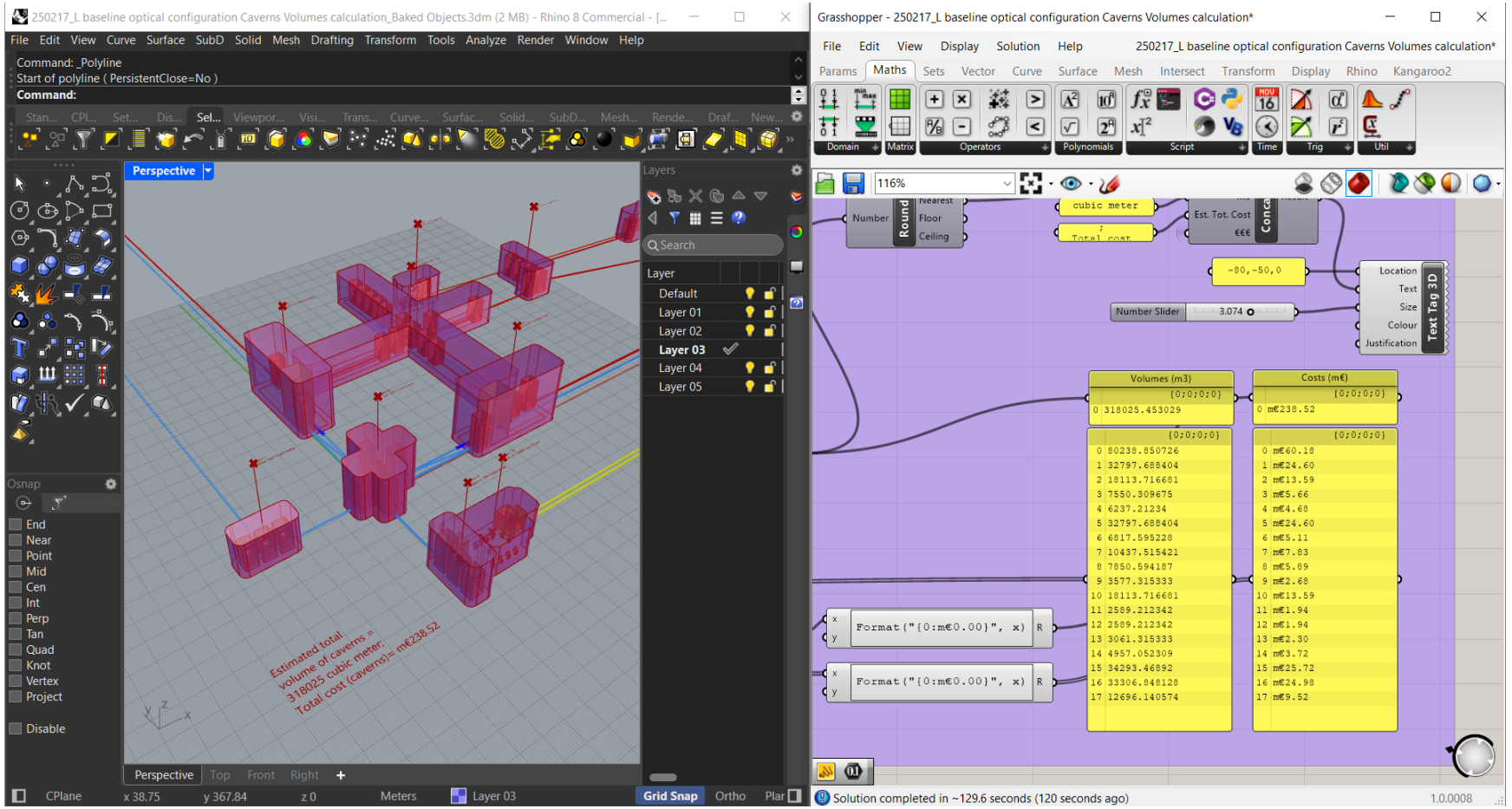


Parametric approach as cost estimation tool

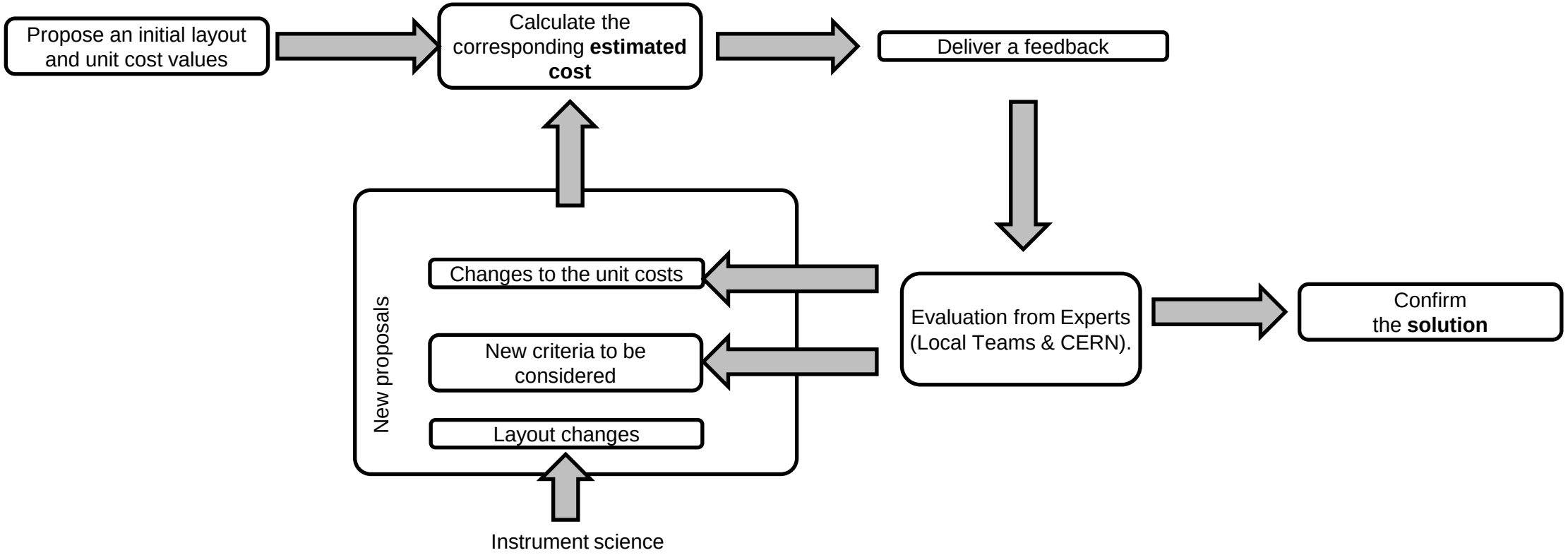


Workflow for cost estimation used during task force activities

Parametric approach as cost estimation tool



Parametric approach as cost estimation tool

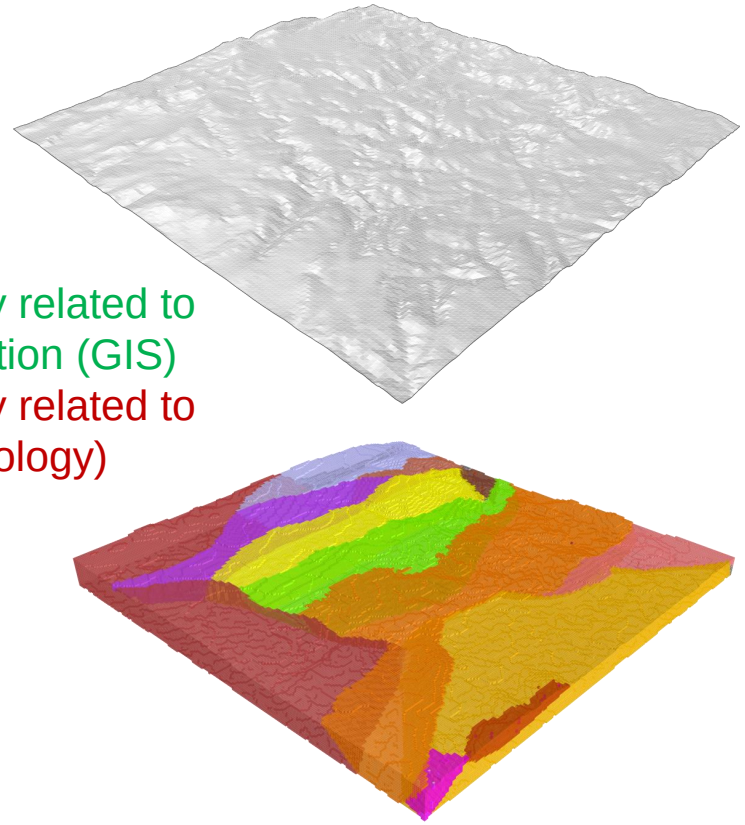


Extending Optimisation Strategies to Enhance Environmental Sustainability Outcomes

Key Sustainability Dimensions for ET as underground infrastructrure

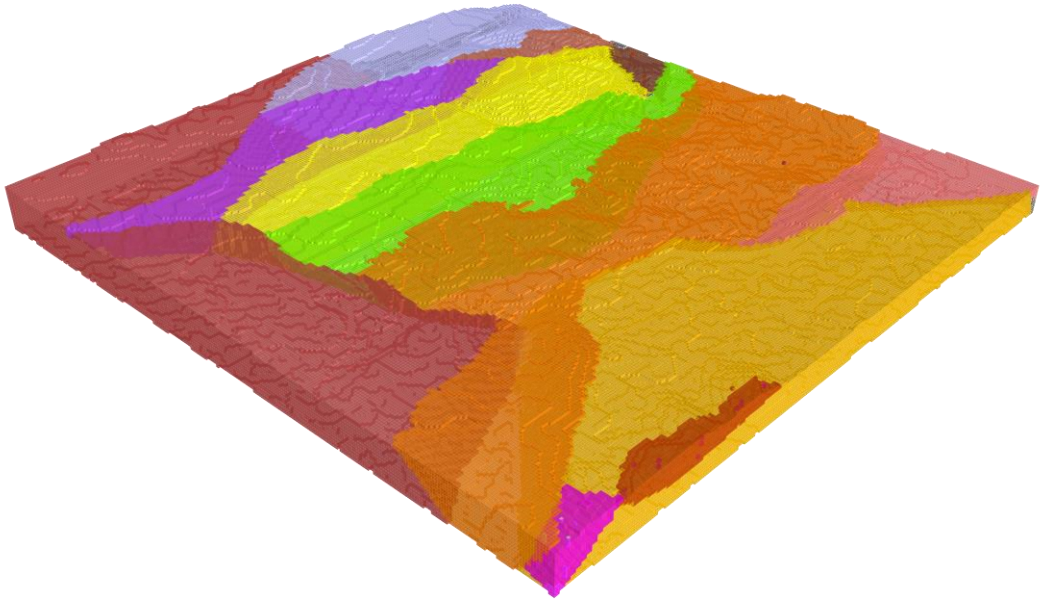
- Supporting infrastructure (roads, electrical infrastructure, …)
- Construction and operational costs
- Excavation methodology and ground support systems
- Energy demand associated with underground works
- Environmental impacts of construction activities
- Material consumption and waste generation
- Carbon emissions and long-term lifecycle performance

… also sustainable tunneling begins with understanding the ground

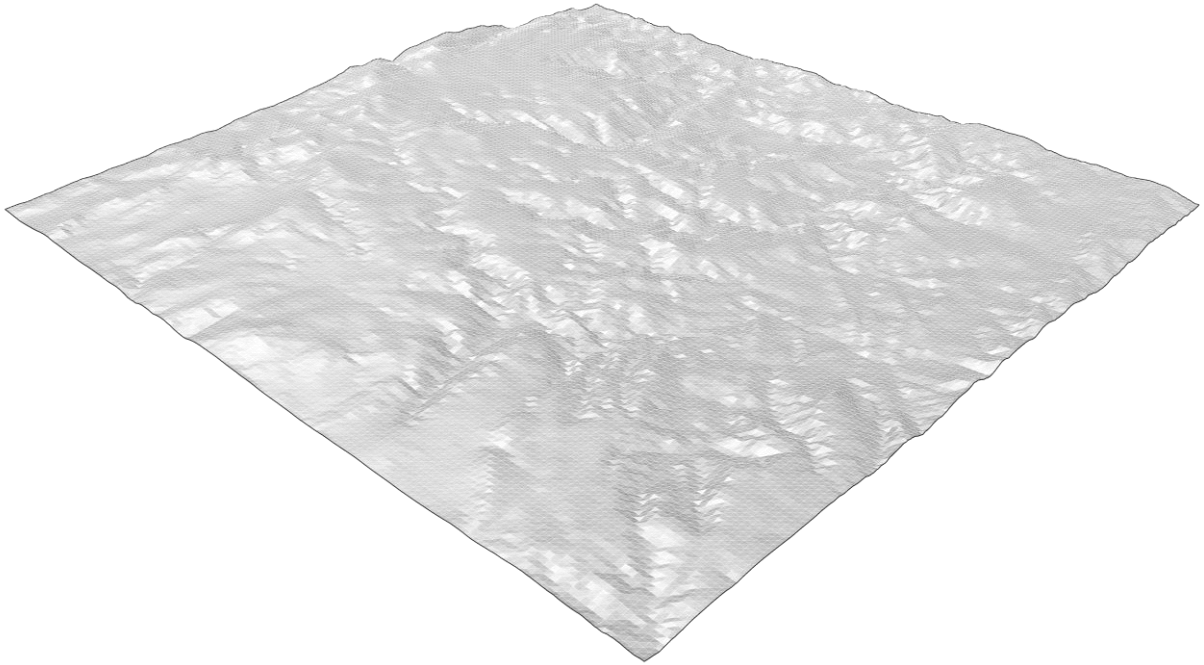


Components mainly related to the surface information (GIS)
Components mainly related to the subsurface (Geology)

Including geology model



Geological model



Digital Terrain Model

A precise geological model enables smarter alignment, less waste, and lower carbon.

Alignment Optimisation

– Avoid faults, weak zones, high water pressure
– Reduce excavation volume and spoil
– Minimize ecosystem disturbance

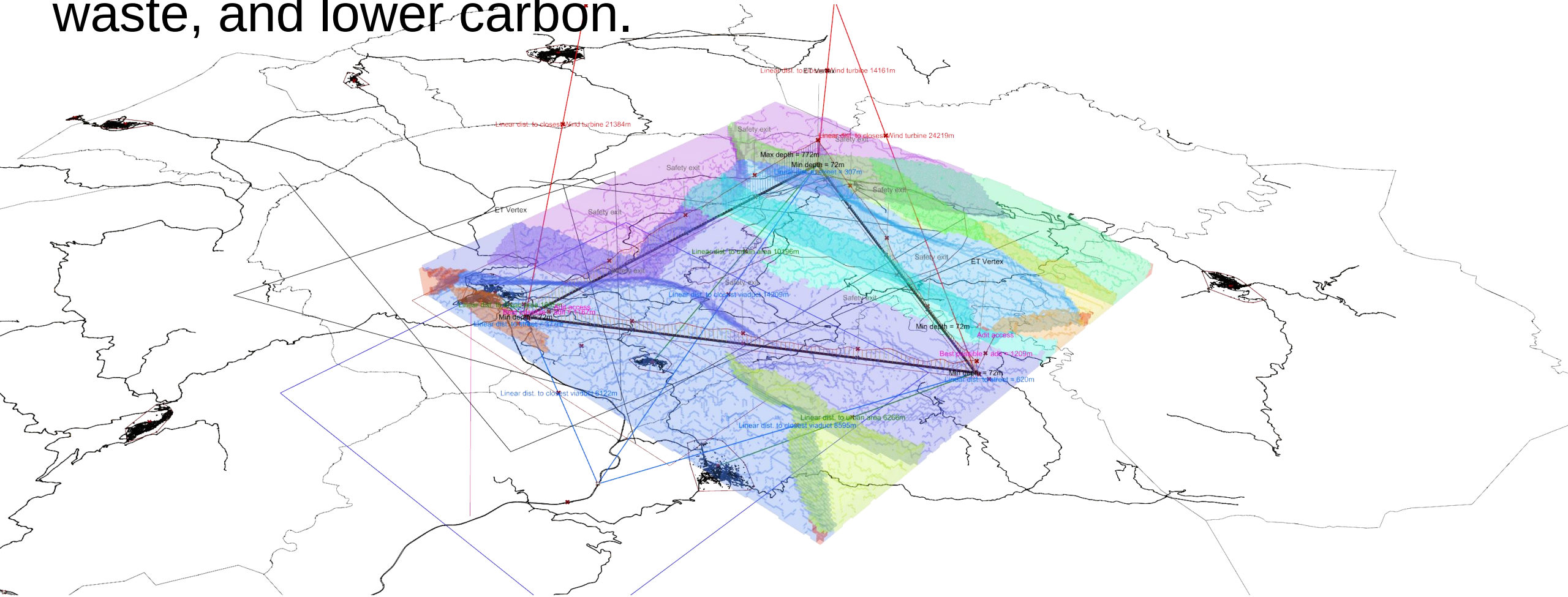
Material & Carbon Reduction

– Rock mass quality → support thickness
– Optimized lining → less concrete & steel
– Lower embodied CO_2

Groundwater Protection

– Control inflow and drawdown
– Protect aquifers and wetlands
– Reduce long-term environmental impact

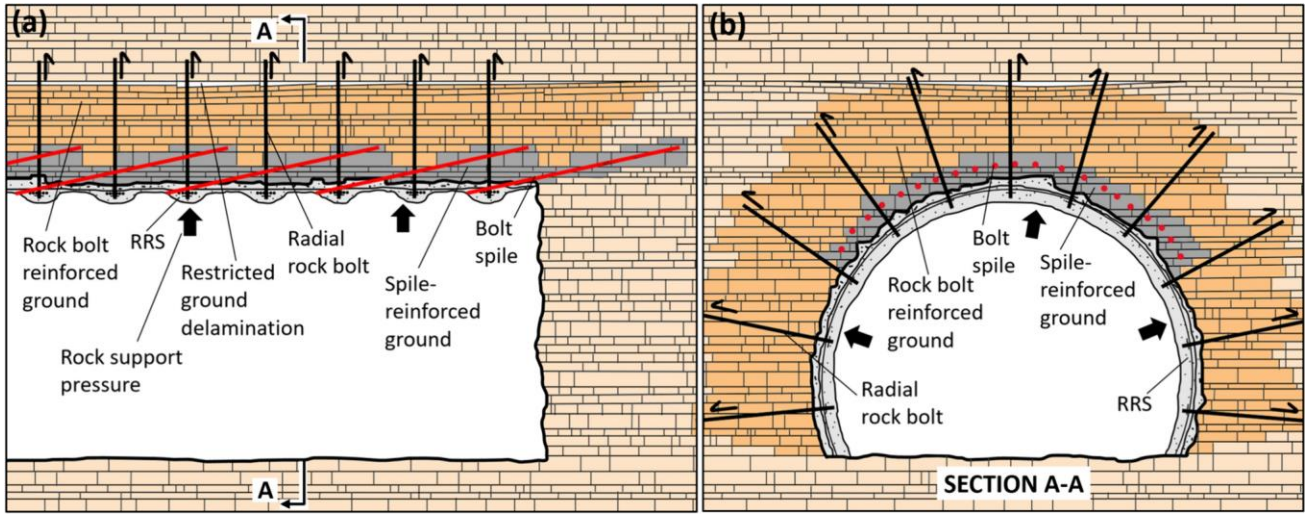
A precise geological model enables smarter alignment, less waste, and lower carbon.



A precise geological model enables smarter alignment, less waste, and lower carbon.

Examples:

- Accurate rock mass classification > thinner linings, fewer rock bolts
- Correct fault and weak zone mapping > localized reinforcement instead of conservative over-design
- Realistic groundwater pressures > optimized waterproofing instead of overbuilt systems



erron-Almenara, J., Skretting, E., Holter, K.G. *et al.* Design of Rock Support in Hard and Layered Rock Masses Using a Hybrid Method: A Study Based on the Construction of the New Skarvberg Tunnel, Norway. *Rock Mech Rock Eng* **57**, 10491–10532 (2024). https://doi.org/10.1007/s00603-024-04082-3

Two levels optimisation strategy for ET placement

A multi-objective optimisation for the placement of ET can generate several optimal solutions.

The primary optimisation level focuses on **performance-critical parameters**, with the highest priority given to **minimising environmental noise** and disturbances as much as possible. Once these performance constraints are satisfied, a second optimisation level is applied, addressing project cost and environmental impact. The set of candidate solutions identified in the first stage is then filtered using a sustainability-oriented criteria set.

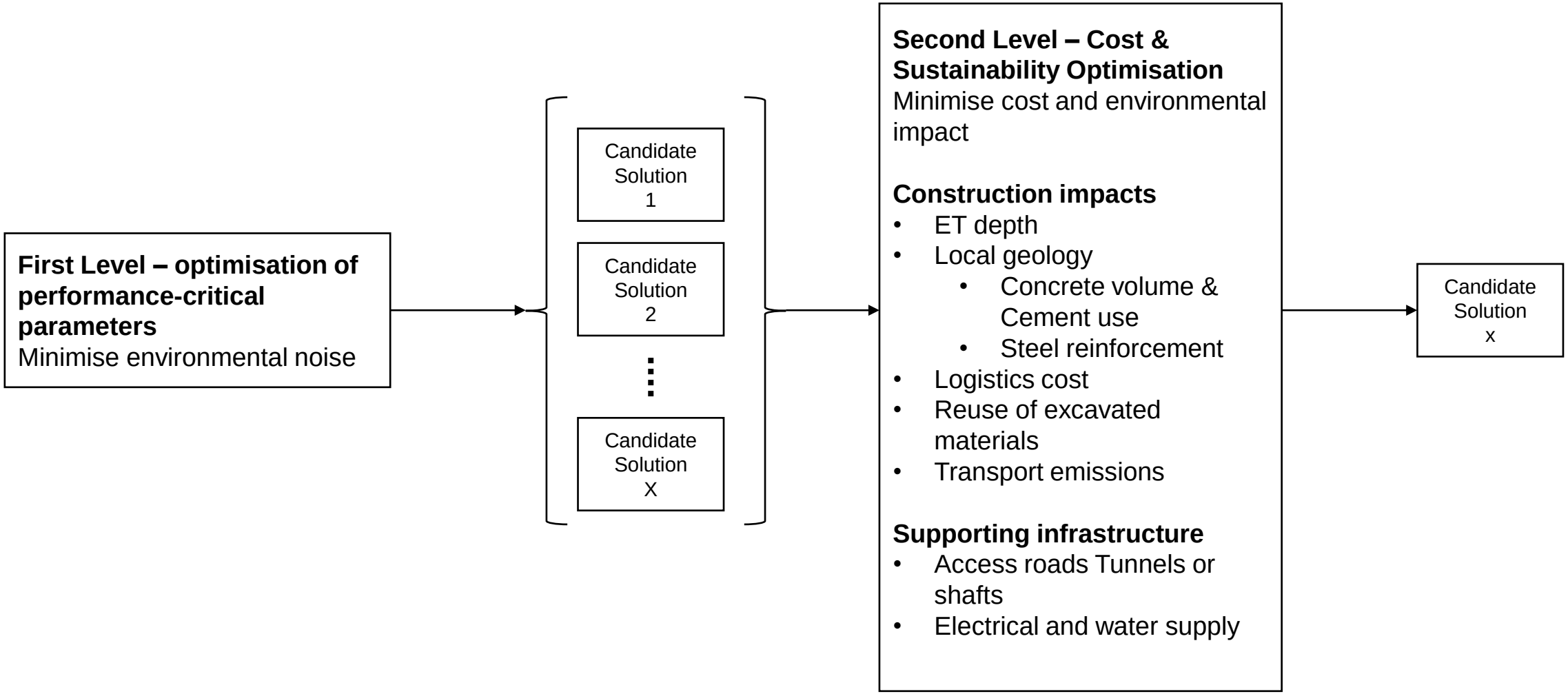
Two levels optimisation strategy for ET placement

Sustainability factors may include:

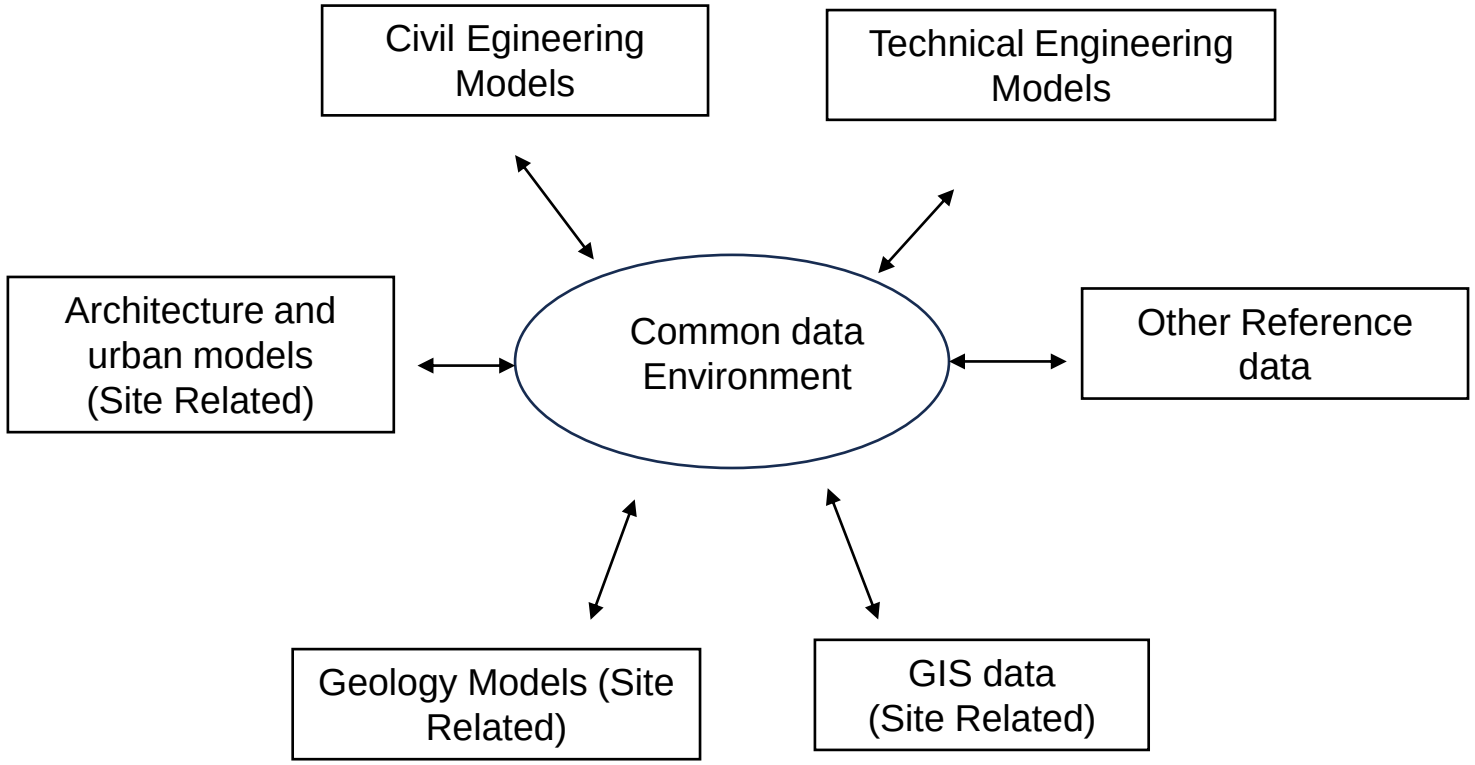
Construction impacts, such as excavation depth, local geology, material types, logistics, and opportunities for reusing excavated materials.

Supporting infrastructure requirements, including the creation or extension of access roads, tunnels or shafts, and the provision of electrical and water supply.

Multi-Objective Optimisation for ET Placement



Sustainable use of digital data and information



Progressive Data Collection as a Sustainable Strategy

Data as a Cumulative Asset

Sustainable infrastructure requires a **progressive and structured data collection process** throughout the project lifecycle.

Key Principles

- Data must be collected incrementally during each phase
- Information must not be lost during phase transitions
- Models should be continuously updated rather than recreated
- Knowledge must be preserved beyond individual project stages

Critical Risk

Fragmented workflows often lead to:

- Loss of geological and geotechnical knowledge
- Disconnection between design and construction data
- Reduced value of models in later phases
- Sustainability depends on continuity of information.

Accumulating Models and Level of Development of the models LOD

From Static Models to Evolving Knowledge Systems

Project models should not remain static representations but evolve by:

- Enriching geological and geotechnical datasets
- Integrating construction monitoring data
- Updating parameters based on real observations
- Increasing the Level of Development of information over time

Progressive Model Enrichment

Design Phase

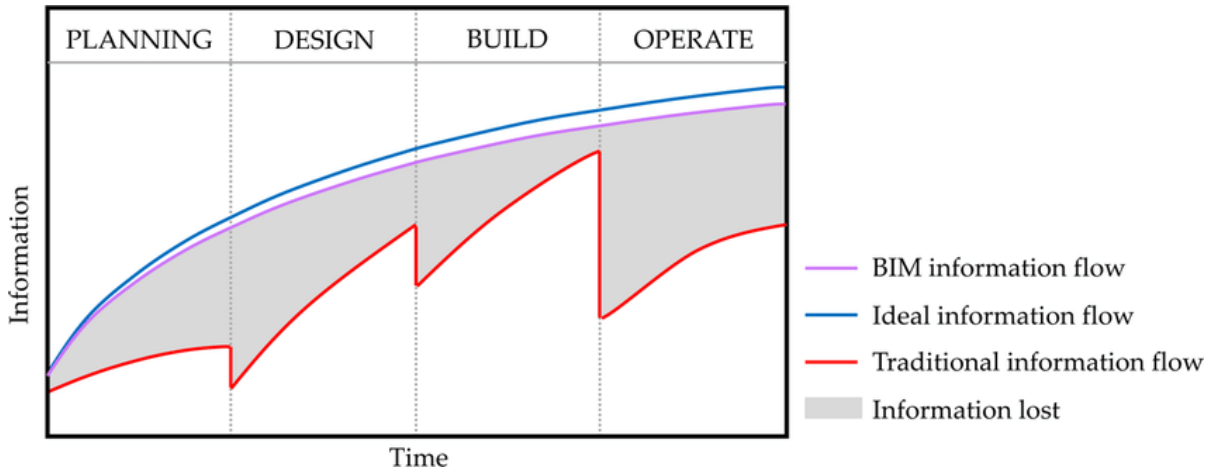
- Conceptual and analytical models
- Initial performance assumptions

Construction Phase

- Field measurements and as-built data
- Calibration of geological and structural models

Outcome:

A validated, higher-value model ready for long-term use.



Pinti, L., & Bonelli, S. (2022). A methodological framework to optimize data management costs and the Hand-Over phase in cultural heritage projects. *Buildings*, *12*(9), 1360.

Decision Aids for Tunneling as example

The Decision Aids for Tunneling (DAT) are an interactive tool that allow one to simulate tunnel construction and determine cost and times of construction including uncertainties associated with geology and construction. The DAT have been developed over the years at MIT, in collaboration with the Ecole Polytechnique Fédérale - Lausanne, and they have been applied to a large number of cases.

The DAT consist of three major components:

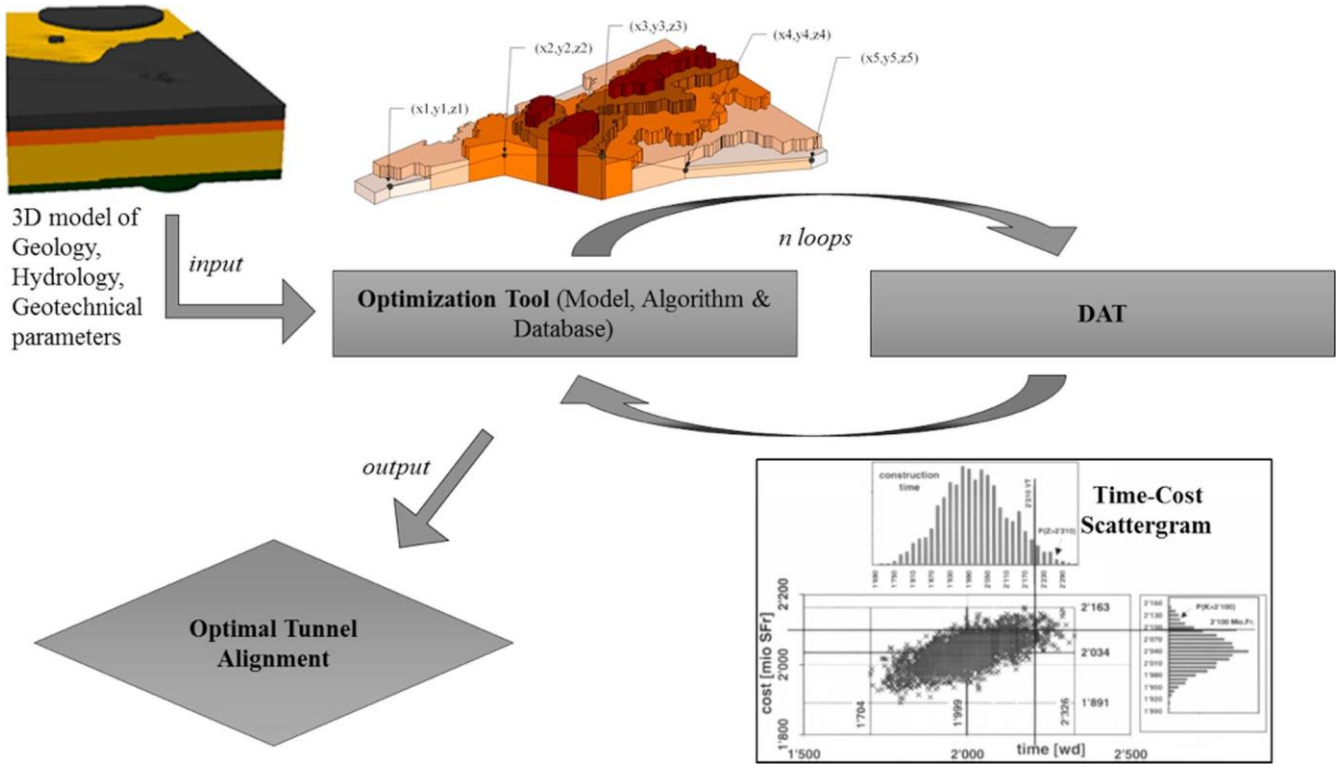
(1). Geology Description

(2). Construction Simulation and Construction (Resource) Management

(3). Updating

Costa, A. L., Sousa, R. L., & Einstein, H. H. (2018). Probabilistic 3D alignment optimization of underground transport infrastructure integrating GIS-based subsurface characterization. *Tunnelling and Underground Space Technology*, *72*, 233-241.

Decision Aids for Tunneling as example



Costa, A. L., Sousa, R. L., & Einstein, H. H. (2018). Probabilistic 3D alignment optimization of underground transport infrastructure integrating GIS-based subsurface characterization. *Tunnelling and Underground Space Technology*, *72*, 233-241.

Conclusion

We propose to enhance the sustainability performance of the project by extending the existing multi-objective optimisation framework to explicitly incorporate sustainability criteria.

This extension requires the integration of high-resolution and comprehensive datasets, including:
Detailed three-dimensional geological models
Advanced geotechnical characterization data
Hydrogeological and environmental parameters

By enriching the optimization process with robust subsurface information, the project can achieve more reliable, resource-efficient, and environmentally responsible design solutions.

Thanks

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