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Bio-inspired algorithm for automated planning of ground investigations along linear construction projects: Balancing impact minimization and regulatory compliance

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ABSTRACT: The increasing demand for green infrastructure, driven by global efforts to transition to sustainable energy, has led to an increase in development of large-scale linear constructions such as high-voltage power lines and pipelines. These projects are often constructed underground to reduce environmental impact. Consequently, reliable and swift execution requires extensive geotechnical investigations, posing significant challenges, starting at their planning. Existing optimization frameworks for automatic placement of investigation sites often rely on computationally expensive simulations of the construction site as objective function for optimization, that don't scale well for national constructions. Instead, this study makes use of suitability maps as a cost-effective method of informing fitness of Ground investigation layouts. The suitability maps primarily describe environmental impact and above-ground risks to timely construction. Quality of geotechnical exploration is only considered indirectly by constraining distances between investigation sites according to national regulations and technical guidelines. This paper presents the use of a multi-agent-system (MAS) as a computationally efficient method for planning geotechnical ground investigations, where each agent models a single investigation site. The decentralized intelligence of the MAS enables balancing individual suitability of investigation sites with standards and regulations through local interaction and "negotiation" with neighboring agents. A case study using a 4.5 km test segment of a linear construction project demonstrates that the algorithm matches or exceeds manual planning performance in terms of compliance with most regulations and guidelines and reduces planning time by 80 to 90 %. Major limitations of the algorithm are the lack of direct consideration of sub-surface site conditions and the segment-wise optimization, causing suboptimal ground investigations at crossover-points between different segments. By shifting the optimization objective from subsurface modeling to above-ground feasibility, this study presents a scalable and practical approach to early-stage geotechnical planning in large scale linear infrastructure constructions.

KEYWORDS: Ground investigation optimization, multi-agent-system, suitability

1 INTRODUCTION

The increasing demand for green infrastructure, driven by global efforts to transition to sustainable energy, has led to an increase in development of large-scale linear constructions such as high-voltage power lines and pipelines. For example, in Germany, the ongoing energy transition involves expedited construction of 16,800 km of new power lines (Bundesnetzagentur 2025) and over 3,600 km of hydrogen pipelines (Bundesnetzagentur 2024). At present, Germany plans to construct this new, green infrastructure underground to minimize impact on the environment and maximize public acceptance. This drastically increases efforts for geotechnical investigations along the entire construction. In addition to the ground investigation program itself, work areas that are to be used during drilling, rescue points for each investigation and access routes to investigation sites from close-by public roads need to be planned as to regulate and minimize impact on nature and land owned by third parties. Ongoing construction projects typically involve up to 2,000 ground investigations per 100 km construction length, pushing available work force for planning and execution of the investigations to its limit. With this, a timely construction of the new, green infrastructure necessitates development of more efficient processes in the planning of geotechnical ground investigations.

Computational optimization of geotechnical ground investigations for linear constructions has hitherto received rather limited attention. Previous studies concentrate on assessment of slope stability, pad footings (Jaksa et al. 2005, Goldsworthy 2006, Goldsworthy et al. 2007) and pile foundations (Arsyad et al. 2009, Crisp et al. 2018). Previous efforts to optimize ground investigations typically involve three key components:

1. Creation of a virtual soil model
2. Assessment of the proficiency and efficiency of geotechnical exploration for any given investigation program
3. Creation of new investigation programs

Virtual soil models typically make use of random field theory (Vanmarke 1983, Fenton and Vanmarcke 1990), owing to the statistical nature of the spatial variability of geotechnical properties. Though multi-layer models exist (Crisp et al. 2020a, Crisp et al. 2021), at present, single-soil-layer models are most common (Jaksa et al. 2005, Goldsworthy et al. 2005, Gong et al. 2014). Investigation programs are assessed by virtually sampling the soil model and creating a new soil model from using only information gained from the investigations. The investigation program is then evaluated using either general, structure agnostic measures like deviation from the original model (Wang et al. 2019, Guan and Wang 2020), model uncertainty (Parsons and Frost 2002, Gong et al. 2014, Huang et al. 2020) or by incorporating the context of the engineering context through random finite element analysis/methods (RFEM) (Fenton and Griffiths 2008) to infer projected construction failure chance and cost (Jaksa et al. 2003, Goldsworthy et al. 2005, Jaksa et al. 2005, Goldsworthy 2006, Goldsworthy et al. 2007, Arsyad 2009, Arsyad et al. 2009, Crisp et al. 2020a, Crisp et al. 2020b, Crisp et al. 2020c, Crisp et al. 2020d, Crisp 2020, Crisp et al. 2021). The generation of new, structure specific investigation programs without human input has hitherto seen little innovation. Crisp et al. (2020c) present a genetic algorithm that optimizes investigation sites for pile foundations using the RFEM. They apply their algorithm to a 40 m × 40 m construction site with a maximum number of 25 investigation sites. Huang et al. (2020) utilize Voronoi tessellation to generate new investigation programs for irregular shaped constructions based on a generalistic optimization goal. They test their algorithm on a 50 m × 80 m construction site with a maximum number of 100 investigation sites.

The methods of scoring investigation programs presented in existing studies aren't applicable for large-scale linear constructions. Neither the approach's optimization target is entirely in-line with the unique optimization targets of large-scale linear constructions nor have the impact of investigation sites on the environment and risks to timely construction been addressed. Additionally, statistical three-dimensional soil models with sufficient resolution and finite element modeling for constructions of multiple 100 km length remain computationally too expensive for practical use. Similarly, the undirected nature of genetic optimization algorithms, coupled with the scale of the linear constructions and the enormous search space limit the usability of the framework of Crisp et al. (2020c) for generating new investigation programs.

This paper aims to bridge the gap between state-of-the-art solutions for optimization of ground investigations in traditional civil engineering and the state of practice in large-scale, continuous linear constructions by proposing a computationally efficient method for planning cost-optimized ground investigations.

2 ASSUMPTIONS

This paper assumes geotechnical ground investigations adhering to the German DIN EN ISO 1997-2 (at least one direct investigation (typically a borehole) every 200 m along the constructions centerline) and to the technical guidelines by the drilling contractor's association (DCA) (at least one direct investigation every 50 - 100 m along horizontal directional drilling (HDD) paths) to be adequately geotechnically explored. With this, the expensive random finite element methods of previous studies are replaced by distance checks between investigation sites.

Investigation types are chosen exclusively based on the construction method. Along open construction sections (trench method), each cluster of investigation sites consists of 3 small diameter drillings and 1 medium dynamic probing. Along closed construction sections (HDDs, microtunnels), each cluster of investigation sites consists of 1 core drilling and 1 heavy dynamic probing. The choice of investigation types is founded in standard practices in ongoing constructions in central Germany and were chosen accordingly to what engineers would normally plan based on national and technical standards.

3 METHODS

3.1 *Suitability modelling*

During planning, engineers typically need to consider numerous different protection zones, existing infrastructure – be it roads, railways, or electricity-, gas- and waterlines – terrain, and plot ownership. Due to federalism in Germany, these requirements might change when crossing state boundaries. Furthermore, some requirements like restrictions due to breeding time of birds are seasonal. In combination with the sheer amount of data layers to be considered and lacking objectivity, this often leads to time-costly planning and may cause human error.

Improving on this, suitability modelling (see Figure 1) is used to introduce an objective measure, encapsulating all requirements and simplifying their complex relationships into a single score, which indicates how suitable any given location is for the purpose of investigative drilling. Suitability, in this case, is a dimensionless value jointly describing the impact on the environment and risk to timely execution.

To this end, all data layers are first rasterized, then scored individually on a common scale and finally aggregated. Rasterization is done by either considering confinement in polygon features like protection zones, or by considering proximity to the closest of a set of features.

Let $P = P_1, P_2, \dots, P_n$ be a collection of polygons

$$R(x,y) = \begin{cases} 1 & \text{if } x,y \in P_i \text{ for } P_i \in P \\ 0 & \text{else} \end{cases} \tag{1}$$

Let $F = F_1, F_2, \dots, F_n$ be a collection of features

$$R(x,y) = \min\left(\sqrt{\left(x - x_{F_i}\right)^2 + \left(y - y_{F_i}\right)^2} \text{ for } F_i \in F\right) \tag{2}$$

The resulting raster data is then scored on a scale of 0 (unsuitable) to 1 (suitable), giving meaning to the input data (e.g. inside protection zone is bad (0), outside protection zone is good (1) or distances < 5 m to railways is bad (0), distances > 10 m to railways are good (1)) (Formulas 4 and 5).

Let $C = C_1, C_2, \dots, C_n$ be a set of minima and maxima $C_i = [\min_i, \max_i]$, where $\min_i, \max_i \in \mathbb{R}$ and $\min_i < \max_i$ and $N_1, N_2, \dots, N_n$ $[0,1]$ are the corresponding suitability scores

$$N(x,y) = \begin{cases} N_1 & \text{if } R(x,y) \in C_1 \\ \vdots & \vdots \\ N_n & \text{if } R(x,y) \in C_n \end{cases} \tag{3}$$

Let $S_G, S_B \in \mathbb{R}$ be threshold values for good and bad suitability scores $N_{Good} = 1$, $N_{Bad} = 0$

$$N(x,y) = N_{Bad} + \frac{N_{Good} - N_{Bad}}{S_{Good} - S_{Bad}} \times (R(x,y) - S_{Bad}) \tag{4}$$

Finally, during aggregation, two types of inputs are differentiated. All data layers that simply inform of preferred and unpreferred areas are aggregated through weighted addition and all data layers that must be completely avoided are multiplied (Formula 5).

Let N_{Add} be the set of all individual suitability scores that describe which locations should be preferred over others and N_{Multi} be the set of individual suitability scores that describe at which locations a total suitability score of 0 must be forced

$$N_{Total}(x,y) = \left(\sum_{i=0}^{N_{Add}} N_i(x,y) \times w_i\right) \times \prod_{i=0}^{N_{Mult}} N_i(x,y) \tag{5}$$

3.2 *Self-organizing multi-agent-system (MAS) optimization*

In this study, optimization follows two goals:

1. Maximization of suitability scores at investigation sites
2. Maximization von distances between investigation sites while assuring compliance with DIN EN ISO 1997-2 and technical guidelines of the DCA (2015)

While optimized positioning of a single investigation site is trivial using the suitability map, the fact that placement of one

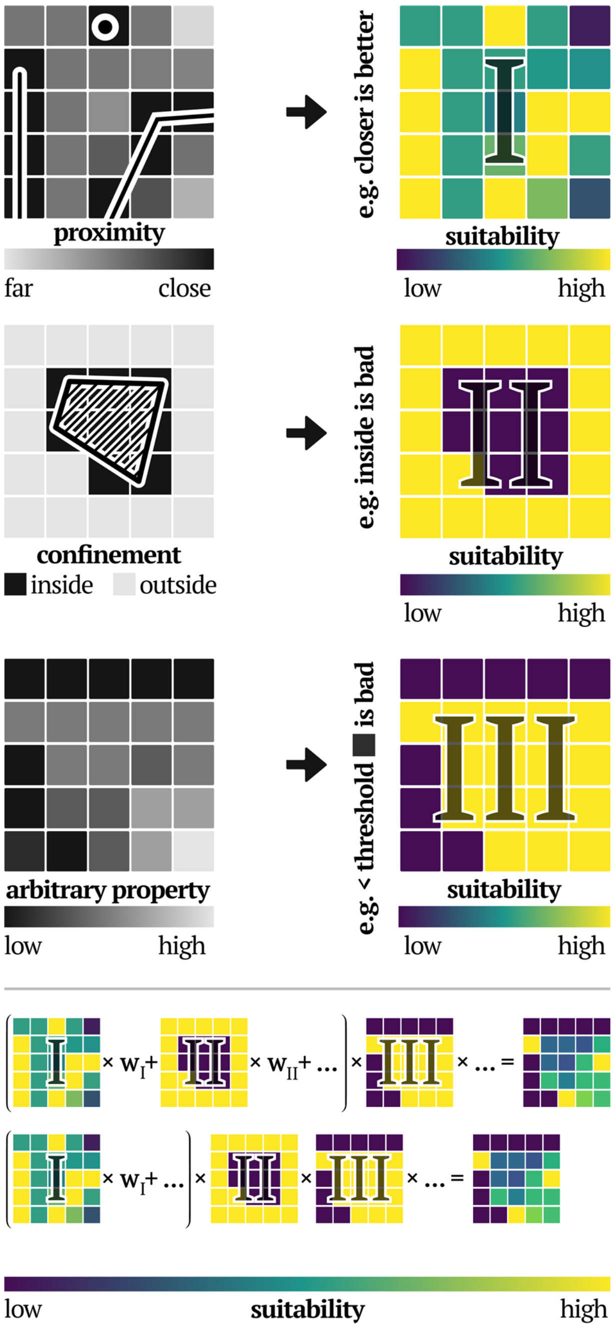


Figure 1. Construction of suitability maps using three principal input layer types (top section): proximity- and confinement-controlled inputs for input data in vector format, as well as distributions of arbitrary properties in raster format. The bottom section shows how completely different suitability maps may be generated from the same input data, by adjusting the weights and/or operator (+ or ×). Generally, input data incorporated by multiplication are more restrictive than input data that are incorporated by weighted addition.

investigation site affects optimal placements of all other investigation sites makes a holistic optimization very complex. Optimal placement of one investigation site may cause sub-optimal positioning of multiple other investigation sites (see figure 2).

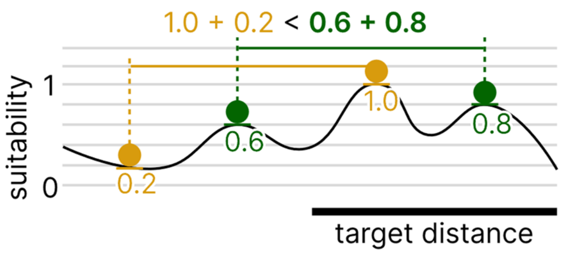


Figure 2. Cross sectional view through a suitability map and positions of investigation sites in two scenarios: In the first scenario (yellow), one investigation site is placed at the highest suitable location, causing the second investigation site to be placed at an unsuitable location, due to constraints on the distance between investigation sites. In the second scenario (green), neither investigation site is placed at the most suitable location. However, the sum of suitability scores in scenario 2 is higher than the sum of suitability scores in scenario 1.

To address this challenge, this paper introduces a self-optimizing MAS inspired by the decentralized, self-organizing behavior observed in natural swarms, such as flocks of birds and annealing-inspired exploration-exploitation scheduling. Rather than relying on centralized coordination, each investigation site operates as an autonomous agent, adjusting its position based on nearby agents and local suitability values. Through this decentralized "negotiation" process, agents effectively compete for more favorable positions while maintaining required spacing. The optimal site-investigation configuration then emerges from local interactions, balancing individual suitability with compliance with standards and regulations.

Figure 3 presents the proposed optimization process. Initially, the construction project is split into continuous segments of equal construction method. As outlined in chapter 2, the construction method directly dictates the required/optimal investigation effort according to regulations and technical guidelines. For each segment, suitability scores are modeled for the space around the construction centerline. Then, an initial set of investigation sites is placed along the construction centerline. The count of investigation sites is determined using the maximum investigation interval and the segment length.

Optimization is driven by applying different forces acting on each agent over several time-steps, until total movement in the system for a given time-step falls below a threshold value or a maximum iteration count is reached. To prevent bias due to order of operations when simulating, the order with which agents are processed is randomized for each iteration and processing is done in two steps. First, a total force is calculated for each agent (Formula 6) and then each agent's movement is simulated using their total force.

$$F_{\mathrm{Tot.}} = F_{\mathrm{Cohesion}} + F_{\mathrm{Separation}} + F_{\mathrm{Suitability}} + F_{\mathrm{Rand.}} \quad (6)$$

F_{Cohesion} and $F_{\mathrm{Separation}}$ are calculated based on the position of the two neighboring agents. If agents are spaced beyond the maximum allowed distance imposed by regulations and standards, a cohesion force draws them closer. Conversely, if agents are spaced closer than the target distance, measured along the construction centerline, they repel each other (Separation). The cohesion force always has greater magnitude than the separation force to ensure maximum distances imposed by regulations and standards are always met. Both forces increase in magnitude throughout the simulation, resulting in better exploration in the beginning and better exploitation at the end of the simulation.

$F_{\mathrm{Suitability}}$ steers agents toward local optima in suitability. Agents determine the most suitable locations within different radii (e.g. 5 m, 20 m and 50 m) and a directional force is applied toward it. Initially, the most suitable location within the largest radius is weighed most heavily to promote exploration and search of global maxima. During the simulation, this bias is then shifted toward the smaller radii, to improve exploitation.

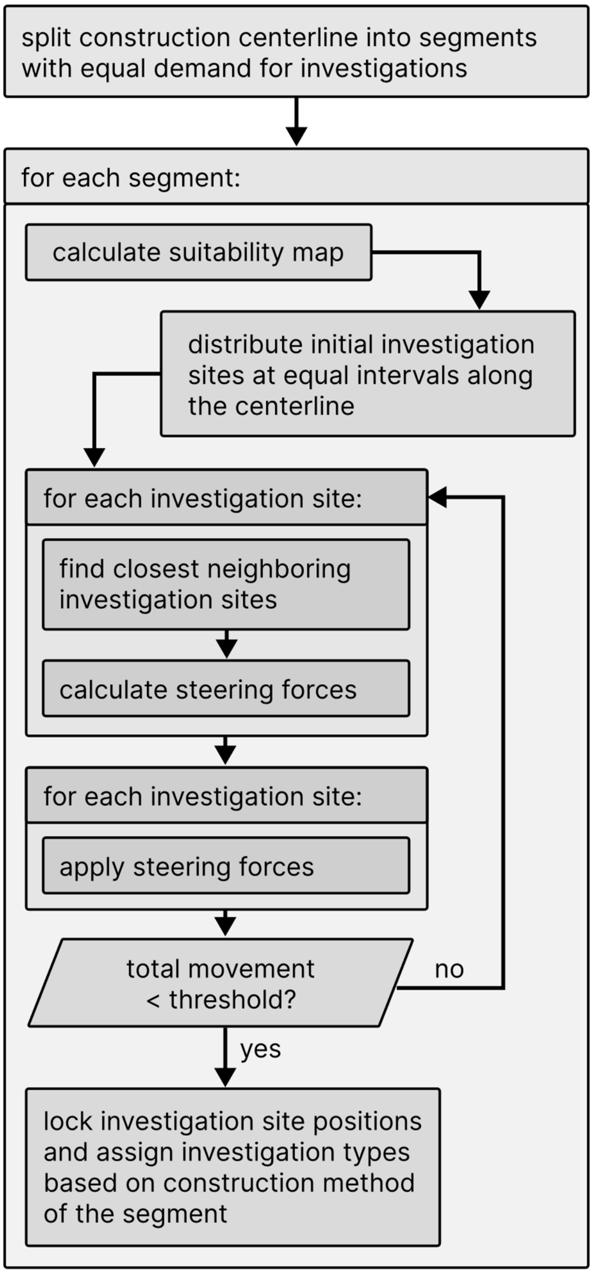


Figure 3. Flowchart detailing the process of the proposed algorithm.

F_{Random} is a strong force applied with low probability to prevent premature convergence on local optima. Both the magnitude and the probability decrease throughout the simulation.

4 ALGORITHM IMPLEMENTATION

The presented algorithm for automated ground investigation planning and the system for usability modeling were implemented as a Python package. The implementation of the algorithms leverages Esri's proprietary Python library "ArcPy" to chain and coordinate existing, highly optimized tools from ArcGIS Pro. The code was executed on a DELL Precision 7540 workstation laptop equipped with an Intel Core i7-9850H processor (2.6 GHz base clock, 4.6 GHz boost clock) and an NVIDIA Quadro T2000 graphics card, running in a Windows environment. It was launched from a Jupyter Notebook within ArcGIS Pro.

5 CASE STUDY

A case study was performed to compare spatial accuracy and speed of the algorithm with manual planning. For this, the time required to generate the site-investigations for a sample linear construction project was measured for both manual and automated planning and both site-investigations were evaluated for compliance with a total of 12 requirements (see Table 1). A distinction must be made between two types of requirements: Compliance with rules, such as avoiding protected areas, can be determined absolutely. Compliance with the second group of requirements can only be assessed relatively between the two ground investigations. These typically involve minimizing or maximizing distances to specific geographic features or optimizing certain indicators.

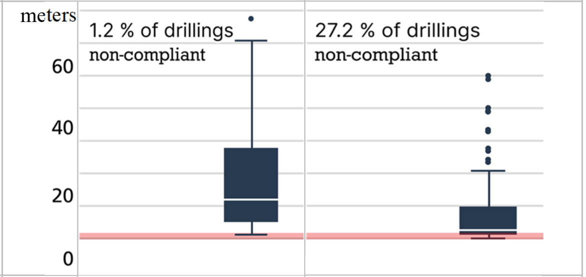
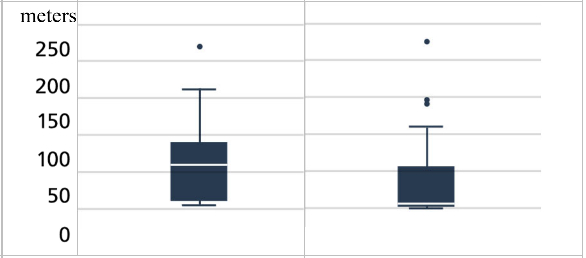
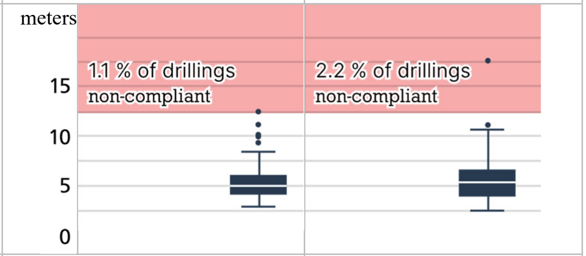
The test site is situated in a rural to peri-urban area in central Germany and has a length of 4.5 km, of which 600 m are planned to be built in closed construction (HDD). The remaining 3.9 km are planned to be built in open construction. The construction's center line has 3 strong bends but remains almost perfectly straight between them. The surrounding area is predominately flat; steep gradients only occur at trenches and ditches alongside farmland boundaries and on embankments next to roads. The immediate vicinity of the construction's centerline is, with exception of a single forest along a 300 m long segment, almost exclusively farmland. The forest is additionally protected by a landscape protection area. Apart from that, the constructions centerline only crosses one more protection zone (soils) and stays clear of most other protection zones. It is to be noted that this is not by chance – generally, protection zones are already considered during the planning of the power line route and are therefore seldomly crossed directly.

Table 2 shows the evaluation of manually and algorithmically planned ground investigations regarding compliance with the guidelines presented in Table 1.

Table 1. Guidelines considered in the suitability map and tested during the evaluation.

No.	Description
I	Maximize % of parcels on public property
II	Maximize investigation sites per parcel
III	Minimize distance to parcel borders but maintain minimum distance of 2 m
IV	Distance to roads (smaller is better)
V	Minimize count of investigation sites withing 3 m of existing electricity, water and gas lines
VI	Minimize count of investigation sites below tree crowns
VII	Minimize count of investigation sites on slopes steeper than 10°
VIII	Minimize count of investigation sites inside landscape protection zones
IX	Minimize count of investigation sites inside water protection zones
X	Minimize count of investigation sites inside soil protection zones
XI	Minimize violations of DIN EN ISO 1997-2 and technical guidelines of the DCA
XII	Investigation sites should alternate the side of the construction's centerline

Table 2. Evaluation results regarding compliance with the tested guidelines.

No.	Manual Planning	Algorithm
I	6.5 %	41.4 %
II	3.94	4.07
III		
IV		
V	0	0
VI	1	0
VII		
VIII	4	2
IX	0	0
X	0	0
XI	0	6
XII	✓	✓
	Time to generate per km construction length	
	600 to 1200 seconds	120 seconds

6 DISCUSSION

6.1 *Results*

The evaluation suggests that ground investigations planned by the proposed algorithm perform on-par or better than manually planned ground investigations regarding compliance with most guidelines and requirements. The algorithmically planned ground investigations show significantly higher use of public parcels, compared to the manually planned ground investigations (requirement I), as well as better minimization of distances to parcel borders and roads (requirements III and IV). Use of the algorithm in a real construction project requires refinement of some of the algorithm's capabilities and configuration:

High non-compliance with requirement III should be mitigated by adjusting the suitability map to discourage positioning investigation sites within a wider buffer around parcel borders as gradient in the suitability map caused by the distance minimization target may lead agents to cross over into low suitable areas during some iterations.

One insufficiency of the algorithm that cannot be fixed through changes to the suitability map is the segment-wise optimization. While this works well on longer, continuous segments, the algorithm quickly loses flexibility on short segments, such as small crossings of existing infrastructure or natural borders. This is detrimental, as optimal ground investigations require the most flexibility in these very scenarios, as the feature to be crossed typically negatively impacts suitability scores and most locations become infeasible. This inflexibility contributes to poor performance regarding requirement VIII at the test-site. However, as linear constructions are large, a global optimization often becomes infeasible due to computational constraints. To compromise, future improvements to the algorithm could be made by making use of overlapping optimization windows, independent of construction type.

Poor performance regarding requirement XI is caused by a systemic methodical error. Distance between investigation sites was determined using direct distance during the simulation of the MAS. This approximation only works for straight construction centerlines and short distances between investigation sites and the construction centerline. However, along bent centerlines, this approximation may cause drastically too short or too large intervals between investigation sites (see Figure 4).

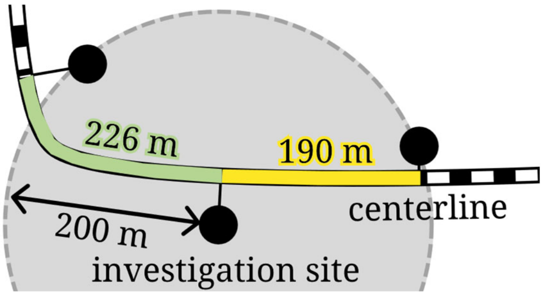


Figure 4. Approximation of distance between investigation sites at curved construction centerlines causes violations of national regulations and technical guidelines.

6.2 *Methodology*

The results of the algorithm are strongly dependent on the quality of the suitability map used. In this study, the weighting of individual suitability layers was chosen heuristically, guided by subjective judgement of the authors and iterative visual inspection of preliminary results. While the algorithm produced satisfactory results, this approach is not optimized or validated using objective measures. Systematic weight calibration using pareto optimization frameworks to balance competing objectives or machine learning on historical planning outcomes could potentially improve quality of the algorithm's outputs. Additionally, a comprehensive sensitivity analysis should be performed to inform the robustness of the planned ground investigations to variation of weights.

Geological ground conditions are not explicitly considered by the algorithm, nor by the evaluation. Instead, it is assumed that adherence to regulations and technical guidelines guarantees sufficient geotechnical exploration. While these regulations and technical guidelines are generalized and designed to be applicable for most construction projects, the minimum investigation efforts they inform should be adjusted based on professional engineering judgement and ground conditions (DIN EN ISO 1997-2). This responsibility is hitherto overlooked by the proposed algorithm. Consequently, future developments of the algorithm should focus on the integration of expected site conditions into the optimization process.

Direct quantification of spatial uncertainty during the optimization process, such as described by Jaksa et al. (2003), is difficult to include in the proposed MAS. The MAS relies on local gradients in a suitability landscape to steer the individual agents, whereas methods such as RFEM typically produce non-local feedback on global fitness of the entire investigation layout and only information only becomes available after the investigation layout is proposed and tested in a simulation.

To balance computational feasibility and tractability of the MAS with intelligent risk awareness of RFEM based methods, a risk-adaptive optimization could be achieved through inclusion of suitability layers representing (hydro-)geological risks (e.g. fault lines, soft soils, karst, high groundwater-levels) during construction of the suitability map. High risk areas are assigned high suitability scores, biasing the algorithm to better explore high risk areas. Additionally, the MAS may be selectively influenced to prefer shorter intervals between investigation sites within risk-prone geological units. Adaption of the suitability map using a-priori geological knowledge and proxies for high-risk areas would offer a practical, computationally cheap solution, enabling ground investigation optimization for large-scale linear infrastructure projects, where swift investigation layout generation is important.

7 CONCLUSIONS

Contrary to commonly used frameworks of ground investigation optimization, that make extensive use of computationally expensive random finite element methods and exclusively consider fitness of geotechnical exploration, this study focuses on above-ground impact and risk minimization.

Despite its current limitations, the proposed approach demonstrates applicability of MAS in ground investigation optimization using suitability maps as an objective function. Both the objective function and the gradient-based optimization are inherently computationally cheaper than statistical modelling of the subsurface and undirected optimization such as the genetic algorithm proposed by Crisp et al. (2020c) and are usable for large-scale linear constructions. While not explicitly tested in this study, suitability map-based MAS may also be used for ground investigation optimization of non-linear constructions.

Finally, the proposed system should not be viewed as a replacement for professional geotechnical expertise, but rather as a decision-support tool. It enables planners to generate baseline site-investigations in less time, improving efficiency and consistency in time-critical early stages of ground investigations.

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