Computational Formalisation of Constructability: A GIS-Based Spatial Conflict Framework for Low-Voltage Utility Network Design

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Abstract

The energy transition is increasing pressure on utility infrastructure projects to be delivered efficiently and at scale. At the same time, integrated delivery approaches are transferring greater design responsibility to contractors, creating opportunities to incorporate construction knowledge earlier in the design process. However, constructability assessments remain largely informal and experience-based, leading to inconsistent evaluations and a risk of overlooking construction challenges. This paper investigates how geospatial technologies can support a more systematic assessment of constructability during the engineering stage of low-voltage utility network projects. Using a Design Science Research approach, a GIS-based Decision Support System (DSS) was developed that formalises constructability knowledge into explicit spatial assessment rules. The prototype combines urban spatial data and project-specific design information to assess route feasibility, workspace requirements, and construction-method constraints. Through rule-based spatial analysis, the system identifies hard, soft, and workflow clashes between proposed cable route designs and their surrounding environment. Demonstration on a real-world project and evaluation with industry practitioners indicate that the approach supports more consistent and transparent identification of constructability issues. The results demonstrate the potential of GIS-based decision support to bridge the gap between experience-based engineering practice and data-driven constructability assessment.

1. Introduction

The ongoing energy transition is placing increasing pressure on subsurface utility (SU) infrastructure projects. Growing demand for network expansion must be accommodated within constrained schedules, complex urban environments, and persistent shortages of skilled personnel. At the same time, integrated project delivery approaches are becoming more common, transferring greater design responsibility to contractors. This shift creates opportunities to incorporate construction knowledge earlier in the design process, but also increases the need for effective coordination between design and construction activities (Arditi et al., 2002).

In this context, constructability, defined as the integration of construction knowledge and experience into planning, design and procurement processes to improve project delivery (CII, 1986), has become increasingly important. When construction requirements are not adequately incorporated during the engineering stage, unforeseen outcomes such as rework and delays can occur (Arditi et al., 2002; Samimpey & Saghatforoush, 2020). In practice, however, constructability assessments in utility projects often remain informal and rely heavily on the expertise of individual engineers and construction managers. As a result, construction-related conflicts may only become apparent during later project stages.

Although digital technologies such as BIM and 4D modelling have been applied to support constructability in the broader construction sector, their application in SU infrastructure has primarily focused on planning, coordination and construction sequencing. As a result, systematic approaches for identifying utility-specific constructability issues during the engineering stage remain limited. To address this gap, this paper investigates how Geographic Information Systems (GIS) can support a more systematic assessment of constructability in SU projects. Following a Design Science Research approach, a GIS-based prototype was developed and evaluated that identifies constructability conflicts through rule-based spatial analysis. The results demonstrate the potential of GIS-enabled automation to support more consistent and transparent constructability assessments during early engineering stages.

The remainder of this paper is structured as follows. First, the concept of constructability is introduced, followed by a review of the limitations of existing tools and methods for assessing constructability in SU projects. Next, the study's methodological approach is described. The subsequent section presents the main results, including the prototype design, a demonstration of its application, and an evaluation by practitioners. Finally, the findings are discussed, and conclusions are drawn.

2. Literature review

This section discusses the concept of constructability, reviews existing assessment approaches, and examines their applicability to SU projects. The resulting research gap forms the basis for the study objective.

2.1 The concept of constructability

Design decisions made during the early stages of a project significantly influence subsequent construction activities and project performance (Arditi et al., 2002; Zolfagharian & Irizarry, 2017). When construction requirements are not

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adequately considered during design, projects may encounter unforeseen implementation challenges that can lead to rework, delays, and reduced productivity (Samimpey & Saghatforoush, 2020). Consequently, considerable attention has been given to the concept of constructability as a means of improving project delivery.

The Construction Industry Institute (CII, 1986) defines constructability as the optimal integration of construction knowledge and experience into planning, design, procurement, and field operations to achieve overall project objectives. The underlying principle is that construction expertise should be incorporated as early as possible in the design process, enabling potential problems to be identified and resolved before construction begins. Through this integration, projects can benefit from improved efficiency, reduced uncertainty, and fewer design-related disruptions during execution (Jergeas & Van der Put, 2001). The literature often uses the term "buildability" alongside "constructability". While some authors distinguish between the concepts, both generally refer to integrating construction knowledge into design to facilitate efficient project execution, consistent with the definition proposed by the CII (Jergeas & Van der Put, 2001; Wong et al., 2007). In this study, the term constructability therefore serves as the overarching concept.

In practice, constructability is commonly operationalised by identifying and assessing constructability factors. These factors are project characteristics, constraints, or conditions that influence the ease and efficiency of constructing a design. Previous studies have identified a wide range of constructability factors, which are often grouped into categories related to design characteristics, construction methods, site conditions, resource availability, and organisational or managerial aspects of project delivery (Faraji et al., 2023; Lam et al., 2006). Assessing these factors allows for the identification of potential constructability issues and opportunities for design improvement before construction begins.

Despite broad agreement on its importance, implementing constructability remains challenging because construction knowledge is often dispersed among individual experts and teams. As a result, constructability assessments frequently depend on professional judgement rather than systematic evaluation methods (Zadeh et al., 2025). This creates a need for approaches that can support the consistent identification of potential constructability issues during design.

2.2 Existing constructability assessment methods

Traditionally, constructability has been assessed through reviews involving designers, engineers, construction managers, and other domain experts. Potential construction issues are identified through manual examination of drawings, design reviews, coordination meetings, and constructability checklists. While these approaches represent established industry practice, their effectiveness depends heavily on the expertise and experience of the individuals involved. To improve consistency and transparency, various structured assessment approaches have been proposed. Early studies focused on constructability checklists and quantified assessment systems that evaluate design alternatives against predefined criteria or performance indicators (Wong et al., 2007). More recently, digital technologies have enabled increasingly automated forms of constructability assessment (Fadoul et al., 2021).

Particular attention has been given to Building Information Modelling (BIM) and 4D modelling environments. BIM supports visualisation, information integration, and design coordination, while 4D models combine design information with scheduling data to represent construction activities over time (Hijazi et al., 2009; Zhang et al., 2016). These technologies have been applied to support construction sequencing, clash detection, schedule optimisation, and multidisciplinary coordination (Olde Scholtenhuis et al., 2016; Yin et al., 2024). Furthermore, BIM-based environments have been used to support broader construction planning activities, including the analysis of logistics, workspace interactions, and construction risks.

The emergence of data standards such as IFC and CityGML has further expanded these capabilities by enabling the integration of infrastructure assets with their surrounding geographic environment, resulting in richer digital representations of projects and their context. Such integrated representations provide a foundation for more advanced forms of analysis, including rule-based assessment systems that translate constructability requirements into computational rules and automatically evaluate designs against predefined criteria (Jiang & Leicht, 2016). These approaches reduce subjective interpretation and support more transparent, consistent, and repeatable constructability assessments.

Although these developments have significantly advanced constructability assessment, most applications continue to focus on building projects and primarily emphasise planning, coordination, and construction sequencing. Consequently, constructability challenges related to the physical project environment, such as site-specific constraints and construction-method suitability, remain comparatively underexplored. This is particularly evident in the SU domain.

2.3 Constructability in subsurface utilities projects

The constructability challenges encountered in SU projects differ from those of traditional building projects. SU infrastructures are linear assets that extend through complex urban environments and must coexist with existing underground and above-ground infrastructure. Their constructability is therefore strongly influenced by local spatial conditions, including existing utilities, road infrastructure, available working space, excavation requirements, and environmental constraints.

Recent developments have extended BIM concepts beyond buildings towards infrastructure applications, including transportation and SU infrastructure. These developments support digital representation, information exchange, coordination, and clash detection throughout infrastructure projects. Several studies have successfully applied BIM and 4D approaches within utility and infrastructure contexts, demonstrating their value for planning, execution sequencing, and project coordination (Olde Scholtenhuis et al., 2016; Yin et al., 2024). However, existing applications primarily focus on temporal and coordination-related aspects of constructability. Their main objective is often to optimise scheduling, construction sequencing, or multidisciplinary coordination rather than to assess the feasibility of construction methods under local site conditions. As a result, many utility-specific constructability challenges remain dependent on manual interpretation by engineers and construction specialists.

Because these challenges are inherently spatial, Geographic Information Systems (GIS) may offer complementary capabilities. Unlike traditional BIM environments, GIS is specifically designed to analyse spatial relationships between assets and their surrounding environment. GIS can integrate geographically referenced data from multiple sources and support spatial analyses that identify conflicts among proposed utility alignments, construction methods, and environmental constraints. Consequently, GIS offers opportunities for more systematic, data-driven constructability assessment during utility design. This study, therefore, investigates how GIS can support constructability assessment in the engineering of SU projects. To address this objective, a GIS-based Decision Support System (DSS) was developed and evaluated for identifying constructability conflicts through rule-based spatial analysis. The methodological approach adopted for this purpose is described in the next section.

3. Methodology

This study adopts a Design Science Research (DSR) approach to develop and evaluate a constructability assessment prototype for low-voltage electricity network design. DSR is particularly suitable because the objective of the research is not only to investigate a practical problem, but also to develop and evaluate an artefact that addresses it. The study is guided by the DSR frameworks of Hevner (2007) and Peffers et al. (2007), which stress the integration of practical relevance, existing knowledge, artefact development, and evaluation. Following the DSR paradigm, the study progressed through the activities of problem investigation, design, development, demonstration, and evaluation in an iterative manner. Feedback obtained throughout the research process was continuously used to refine requirements, underlying assumptions, constructability rules, and prototype functionality. As such, artefact development evolved through successive refinements informed by both theoretical insights and practitioner feedback.

3.1 Case setting and design process

The research was conducted in collaboration with a Dutch infrastructure contractor responsible for designing and constructing SU infrastructure for Dutch Distribution System Operators. The study focused on neighbourhood-oriented low-voltage reinforcement projects that form part of the ongoing energy transition. Within these projects, constructability considerations are often incorporated through engineering experience, field verification activities, and technical guidelines. However, a structured approach to assessing constructability during the early engineering stages is largely absent, creating opportunities for decision support during the design process.

The research began with a problem investigation phase aimed at understanding the organisational context, current workflows, and constructability challenges. Six observation sessions were conducted across different project stages, including early design, field verification, and active construction projects. These observations were complemented by informal discussions with engineers, CAD specialists, and construction managers. The observations were used to identify how constructability is currently considered in practice, where challenges emerge, and at which stages of the design process support would be most valuable. Notes and summaries were analysed to identify recurring themes that informed the initial problem definition and solution requirements.

Subsequently, a knowledge acquisition phase was conducted to identify and validate constructability factors relevant to low-voltage network projects. Six semi-structured interviews were conducted with practitioners, comprising three engineers and three construction managers. The interview protocol was informed by the constructability factors identified in the literature review. Participants were asked about factors that influence constructability, common issues encountered during project execution, and how constructability considerations are currently incorporated into design decisions. While engineers were primarily asked about design practices and decision-making processes, construction managers were asked to reflect on practical challenges arising during construction. Interview transcripts were analysed using thematic coding, combining categories derived from the literature with themes that emerged from practitioners' experiences.

To further develop the knowledge base, the interview findings were complemented with document analysis. Relevant engineering guidelines, construction standards, and organisational procedures were reviewed to identify formal requirements, technical constraints, safety considerations, and design rules. Together, the observations, interviews, and document analysis were used to establish the knowledge base that informed the prototype design.

The prototype development phase translated the identified constructability factors into GIS-based assessment rules. Constructability factors were evaluated against available spatial datasets to determine which factors could be operationalised within a GIS environment. Throughout development, intermediate versions of the prototype were regularly discussed with supervisors and domain experts. These discussions focused on the validity of assumptions, the feasibility of data requirements, the interpretation of constructability rules, and the usability of outputs. Feedback from these interactions frequently led to revisions to design choices and analytical procedures, illustrating the iterative nature of the development process.

Finally, the prototype was demonstrated and evaluated using a real-world low-voltage reinforcement project in the Netherlands. The demonstration aimed to assess the prototype's applicability in an authentic project setting and to generate realistic use cases. The resulting outputs were subsequently discussed during a focus group involving the participating engineers and construction managers. During the session, the prototype workflow and outputs were presented, and participants were invited to discuss the usefulness, completeness, accuracy, ease of use, and presentation of the results. In addition, participants completed a short questionnaire to capture their individual assessments. The feedback obtained during the evaluation was analysed against the predefined criteria and used to assess the artefact's practical value.

3.2 Ethical considerations

Ethical considerations were addressed throughout the study. Prior to participating in interviews and the focus group, all participants received an explanation of the research objectives, the intended use of the collected data, and the voluntary nature of their participation. Participants were informed that they could withdraw from the study at any time without consequences. Written informed consent was obtained from all participants before data collection commenced. As part of the member-checking process, summaries of the interview transcripts were returned to participants to verify the accuracy of the recorded information and their agreement with its use in the study. To ensure confidentiality, interview transcripts, focus group recordings, and questionnaire responses were anonymised during analysis and reporting. All collected data were used exclusively for academic research purposes.

4. Artefact development and evaluation

This section presents the developed constructability assessment prototype and its evaluation. First, the prototype design is described, including the underlying knowledge base, data requirements, and reasoning. Subsequently, the prototype is demonstrated using a real-world project and evaluated through practitioner feedback.

4.1 Prototype design

4.1.1 System requirements and design principles

The prototype was designed to support constructability assessment during the engineering stage of low-voltage electricity network projects. Interview findings showed that constructability issues are often caused by interactions between the planned cable route, local environmental conditions, and the construction methods used to realise the design. To address this challenge, the prototype adopts a rule-based DSS approach that translates constructability knowledge into explicit and reusable assessment rules. By combining these rules with geospatial data, constructability can be evaluated systematically rather than through manual inspection alone. The resulting architecture consists of: (1) a knowledge base containing constructability rules; (2) a data management module providing the required environmental and project-specific information; and (3) a reasoning engine that applies the rules through spatial analysis to generate constructability assessments (Figure 1).

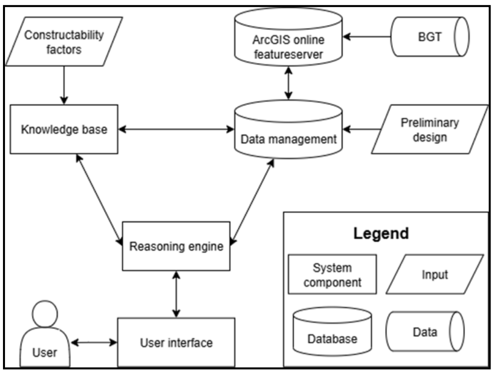

Figure 1. DSS system architecture.

4.1.2 Knowledge base and rule formalisation

The interviews identified a broad range of constructability factors. However, many factors were found to be specific to earlier or later project stages and could therefore not be assessed during early design and engineering. Consequently, the knowledge base focuses on factors that directly influence route feasibility and can be represented using spatial data. This led to the identification of five categories of assessment rules: (1) minimum-distance requirements to façades, trees, waterbodies, and private boundaries; (2) restrictions determined by pavement type, such as open versus closed surfaces; (3) construction-method constraints, including workspace requirements for open excavation; (4) entry-zone requirements for trenchless techniques such as impact ramming; and (5) conditions that elevate constructability risk when recommended clearances are not maintained.

To translate qualitative constructability knowledge into computationally assessable GIS rules, each constructability factor was decomposed into a geographic object, a spatial relationship, and an assessment threshold. For example, practitioners indicated that new cable installations should maintain a minimum distance from building façades. Because façade geometries are typically unavailable, building footprints are used as a proxy and buffered by the prescribed clearance distance (0.9 m), creating a restriction zone. Similar object-specific buffers are generated for trees, waterbodies, and other distance-based restrictions. The proposed utility route is subsequently evaluated against these restriction layers to identify locations where the planned alignment violates recommended clearances or enters prohibited areas. Table 1 summarises the buffer distances implemented within the prototype.

Category	Object	Buffer distance
Buildings	Buildings	0.9 m
	Other roofed structures	0.9 m
Infrastructure (above ground)	Closed paved roads	-
	Other paved roads	-
	Main roads	0.5 m
	Railways	5.0 m
	Well covers, valves	0.3 m
	Walls, fences	-
Infrastructure (below ground)	Subsurface garbage disposal	2.0 m
Non-vegetated areas	Pavements	-
	Waterbodies	1.0 m
	Water banks	-
Vegetated areas	Vegetated areas	-
	Trees	Tree canopy or > 1.5 m
Non-physical boundaries	Private property	0.3 m

Table 1. Constructability buffer distances.

In addition to route-based restrictions, the knowledge base contains construction-method restrictions. Interviews indicated that constructability depends not only on the location of the proposed cable route, but also on the spatial claim and suitability of the selected construction method. Consequently, the knowledge base includes rules describing trench dimensions, workspace requirements, construction-method suitability, and trenchless crossing requirements. For example, closed pavement types such as asphalt generally restrict the use of open excavation techniques and instead require trenchless construction methods. These method-specific constraints are explicitly represented within the knowledge base and incorporated into the assessment process.

For open excavation, the trench width depends on the number of cables installed. Based on engineering guidelines and practitioner knowledge, trench width is estimated as:

$$wt = 0.3 + (n - 1) * 0.1 \tag{1}$$

where wt = trench width (m)
n = the number of cables installed

The workspace required to execute excavation activities extends beyond the trench itself. Interviews indicated that excavated material cannot be placed directly adjacent to the trench due to

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stability and safety considerations. Consequently, a profile-free space (PFS) of 0.65 m is maintained between the trench edge and the excavated material. In addition, excavated soil expands in volume after excavation. To account for this bulking effect, a factor of 20% was assumed for sandy soils. The required horizontal workspace is therefore estimated as:

$$hw = PFS + \frac{wt * dt * f}{h} \quad (2)$$

where *hw* = horizontal workspace (m)
PFS = profile free space (m)
wt = trench width (m)
dt = trench depth (m)
f = bulking factor soil
h = height outcoming soil (m)

However, constructability depends on the total spatial extent of the trenching operation rather than the space required for the excavated soil alone. Because the cable alignment represents the centreline of the trench and excavated soil is stored on only one side of the excavation, the required space on the excavation side consists of the horizontal workspace plus half of the trench width. The total required space is therefore calculated as:

$$trs = (wt * 0.5) + hw \quad (3)$$

where *trs* = total required space (m)
wt = trench width (m)
hw = horizontal workspace (m)

Figure 2 illustrates the relationship between trench width, profile-free space, excavated soil, and the resulting total workspace requirement. For a trench width of 0.60 m, which accommodates four low-voltage cables, the calculated total required space is approximately 2.03 m.

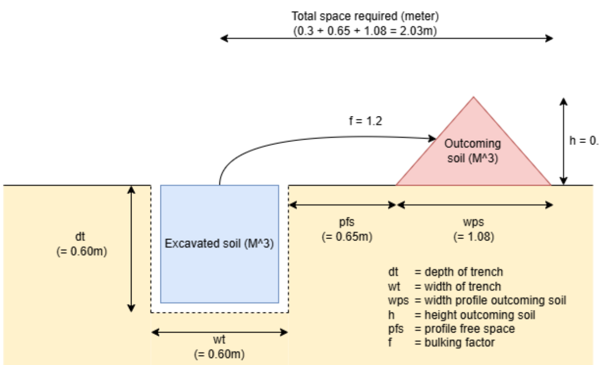

Figure 2. Schematic illustration of the total required space for open trenching.

For trenchless crossings using impact ramming, interviews indicated that approximately 5.5 m of setup space is required to accommodate both the protective tube and installation equipment. This requirement is also explicitly represented within the knowledge base and forms part of the subsequent assessment process.

4.1.3 Data model and information requirements

The prototype combines environmental data describing the existing project surroundings with project-specific engineering data describing the proposed cable route. The required environmental information largely corresponds to CityGML concepts describing buildings, transportation infrastructure, vegetation, water bodies, and land-use objects. Features such as roof structures, building interiors, and energy-related building properties were not required because constructability assessment is performed at or below ground level and depends on horizontal spatial relationships. Table 2 summarises the required spatial objects, attributes and geometry types.

Object	Attribute	Geometry type
Buildings	Geometry, object type	Polygon
Roads	Geometry, pavement type, function/object type	Polygon
Railway	Geometry, function/object type	Line
Waterbodies	Geometry, waterbody type	Polygon
Water banks, ditches	Geometry, object type	Polygon
Vegetated areas	Geometry, vegetation type	Polygon
Paved areas	Geometry, pavement type	Polygon
Trees	Geometry, object type	Point
Manholes	Geometry, object type	Point
Subsurface garbage disposals	Geometry, object type	Point
Private/public land	Geometry, landownership	Polygon

Table 2. Required geospatial objects and attributes used by the prototype.

In addition to the environmental data, the prototype requires a representation of the proposed low-voltage network design. Figure 3 presents the conceptual UML model used for this purpose. The model represents the engineering design as a collection of cable and protective-tube objects linked to a project-specific cable route. While this information can largely be mapped to existing CityGML concepts, several additional attributes are required to support constructability assessment and are therefore introduced as project-specific extensions. These additional attributes include: (1) the number of cables installed within a trench, (2) the excavation side used for temporary storage of excavated material and equipment, and (3) the selected construction method. Together, these attributes enable the prototype to calculate trench dimensions, workspace requirements, and construction-method-specific spatial claims. As these engineering characteristics are not represented within standard CityGML schemas, they are maintained as additional project attributes within the internal data model.

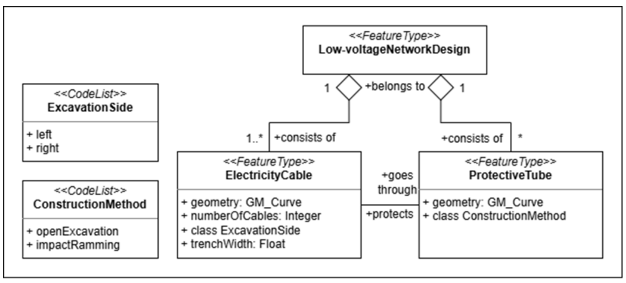

Figure 3. Conceptual UML model of the project-specific low-voltage network design.

In the Dutch implementation of this study, the required environmental information is primarily obtained from the national BGT dataset and its IMGeo extensions. The BGT was selected because it provides harmonised semantics and object classifications throughout the Netherlands, enabling rule-based assessment to be applied consistently across municipalities. The required information was, however, mapped to generic CityGML concepts, illustrating that the proposed approach is based on transferable urban information requirements rather than a specific national dataset.

4.1.4 Reasoning engine and assessment workflow

The reasoning engine operationalises the constructability knowledge stored within the knowledge base through GIS-based spatial analysis implemented in Python and ArcPy. Using the rules, thresholds, and calculations described in the previous sections, the assessment workflow consists of four main steps: (1) construction-space representation; (2) restriction-layer generation; (3) spatial conflict detection; and (4) conflict classification.

During the first step, the knowledge-base rules are applied to the project-specific attributes to generate polygons representing the trench, excavation workspace, and trenchless setup areas. These polygons represent the actual spatial claim of the planned construction activities. During the second step, environmental datasets are transformed into restriction layers based on the assessment rules stored within the knowledge base. During the third step, the generated construction-space polygons are intersected with the restriction layers. Each intersection represents a potential constructability conflict between the proposed design and environmental constraints.

Finally, identified conflicts are translated into clash points and enriched with additional information, including object type, conflict description, urgency, and status. Three categories of clashes are distinguished: (1) hard clashes, representing direct intersections with physical obstacles or prohibited areas; (2) soft clashes, representing violations of recommended clearances or minimum distances; and (3) workflow clashes, representing insufficient workspace for the selected construction method.

4.2 Demonstration

The prototype was demonstrated using a low-voltage reinforcement project in the Netherlands. The project contains a combination of road crossings, vegetation, buildings, and constrained public spaces, providing a representative environment for evaluating the proposed assessment approach. Following execution of the assessment workflow, the prototype generated a constructability assessment layer containing all identified conflicts. For the selected project area, a total of 96 constructability conflicts were identified. The output consists of spatially referenced clash points enriched with information on conflict type, affected object, urgency, and status. Figure 4 shows a representative extract of the assessment results, illustrating the distribution of hard, soft, and workflow clashes along a planned cable route.

The visualisation allows engineers to quickly identify locations requiring further attention and to inspect the underlying causes of individual conflicts. For example, Figure 5 highlights a planned road crossing realised using impact ramming. While the crossing itself is technically feasible, the prototype identified a workflow clash because the workspace required for the installation equipment partially overlaps with a private property boundary. This information can help the engineer select a more suitable setup location before construction commences.

The prototype also supports the identification of unsuitable crossing methods. Figure 6 shows an example where a planned trench intersects a closed pavement section without an appropriate trenchless solution. The conflict is automatically classified as a critical hard clash because construction would require either pavement removal, route adaptation, or a different construction method.

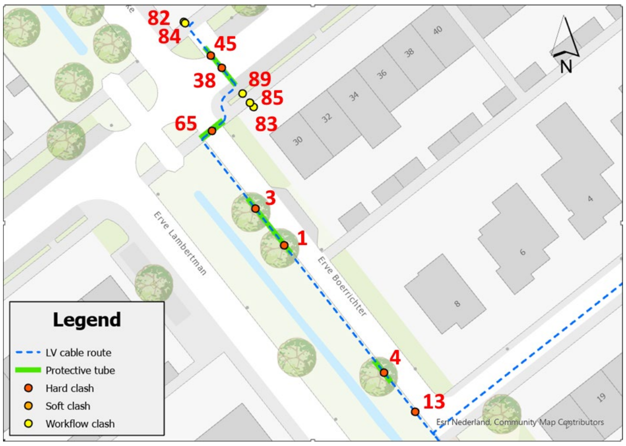

Figure 4. Example constructability assessment results for a cable-route segment.

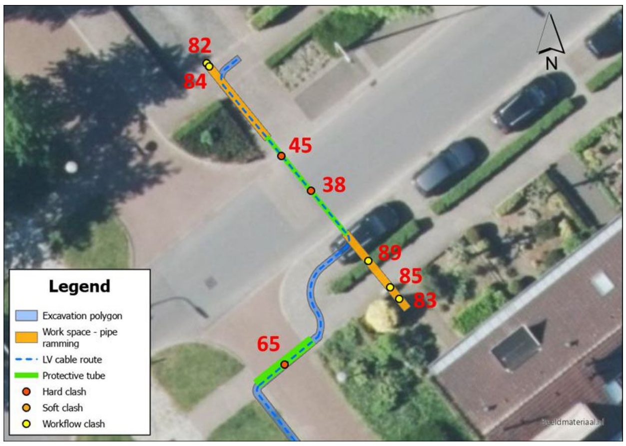

Figure 5. Workflow clash caused by insufficient space for impact-ramming equipment.

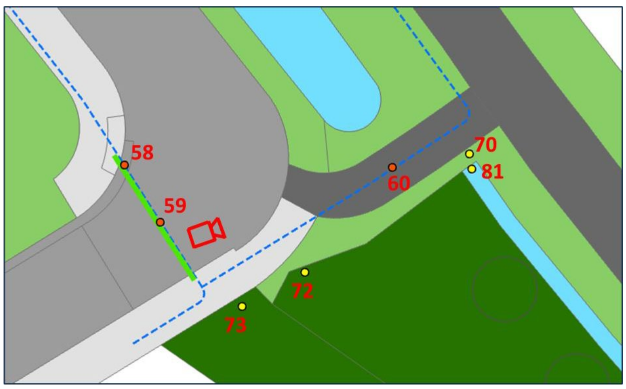

Figure 6. Hard clash resulting from a closed-pavement crossing.

4.3 Evaluation

The prototype was evaluated through a focus group involving three engineers and three construction managers with experience in low-voltage reinforcement projects. Participants assessed the prototype using five predefined criteria: (1)

usefulness, (2) completeness, (3) accuracy, (4) ease of use, and (5) presentation quality.

Overall, participants evaluated the prototype positively, with average scores of 4.1/5 for usefulness, 3.8/5 for completeness, 4.1/5 for accuracy, 3.5/5 for ease of use, and 4.2/5 for presentation quality. Practitioners particularly valued the systematic identification of constructability issues, the visualisation of workspace requirements, and the ability to obtain a project-wide overview of critical locations. Several participants indicated that the prototype could improve consistency across projects and provide additional support for less-experienced engineers.

The most frequently suggested improvement was the integration of existing SU information, such as Dutch KLIC datasets, which could be incorporated as additional restriction layers to assess underground congestion and utility conflicts. While KLIC is a Dutch utility information exchange system, its data model aligns with the European INSPIRE Utility and Governmental Services specifications, enabling conceptual extension to other INSPIRE-compliant utility datasets. Other suggestions included: (1) support for additional construction methods, such as guided drilling, (2) further automation of CAD-to-GIS preprocessing steps, and (3) making the constructability parameters configurable by users to accommodate differences in engineering guidelines between utility providers.

Importantly, practitioners viewed the tool as a complement to engineering expertise rather than a full replacement for field inspection. While the prototype supports the early identification of constructability issues during office-based planning, participants indicated that site inspections remain necessary to verify conditions that are not fully captured in available datasets. This observation also highlights a key limitation of the current approach, namely, the dependence on the completeness and quality of available spatial data. Nevertheless, participants agreed that the prototype provides a valuable basis for more systematic and transparent constructability assessment during the engineering process.

5. Discussion

This study developed and evaluated a GIS-based constructability assessment prototype for low-voltage utility network design. The results demonstrate that constructability knowledge can be formalised as explicit spatial rules and operationalised in a GIS environment to systematically identify conflicts between a proposed cable route, construction methods, and the surrounding urban environment. By translating practitioner knowledge and engineering guidelines into computable rules, the prototype supports a more transparent and consistent constructability assessment process during early design.

From a scientific perspective, the study contributes to constructability assessment literature, which has predominantly focused on BIM- and 4D BIM-based approaches (Vilventhan et al., 2020; Yin et al., 2024; Zhang et al., 2016). While these approaches have demonstrated value for construction planning and coordination, the presented prototype illustrates the complementary role of GIS and urban geospatial data in assessing constructability within its broader spatial context. The study demonstrates how constructability factors can be translated into explicit spatial rules and linked to standardised urban datasets, thereby creating a repeatable assessment framework that extends beyond purely experience-based reviews.

A second contribution concerns interoperability, transferability, and extensibility. Although the prototype was implemented using Dutch datasets such as BGT, the required information was intentionally mapped to generic concepts defined in CityGML and related urban information models. This provides a semantic foundation that facilitates interoperability with other urban datasets and standards, such as INSPIRE-compliant datasets and OGC utility network models. Consequently, the proposed approach is not tied to a specific dataset, utility provider, or national context. Furthermore, the mapping to CityGML offers opportunities to enrich the framework with additional semantic and three-dimensional information on buildings, transportation infrastructure, vegetation, terrain, and SU infrastructures. Such information could support more advanced constructability analyses and provide a pathway towards more comprehensive digital-twin-based decision support environments.

The relevance of such richer urban representations becomes apparent when considering utility construction as a multi-system urban intervention. Constructability is influenced not only by the planned cable route, but also by interactions with transportation infrastructure, vegetation, private property, existing utilities, and available workspace. Future extensions could incorporate additional dimensions such as traffic management, road-surface restoration requirements, underground utility congestion, soil conditions, and stakeholder impacts. Integrating these factors would allow constructability assessment to better reflect the wider urban consequences of infrastructure interventions.

The findings also highlight the importance of data quality for practical deployment. The reliability of the assessment depends on the completeness, accuracy, and timeliness of the underlying spatial datasets. Missing information on trees, street furniture, private property boundaries, or utility assets may lead to incomplete assessments and undetected conflicts, while outdated datasets may no longer accurately reflect site conditions. Consequently, the prototype should be regarded as a decision support tool rather than a replacement for site inspections. Practitioner feedback confirmed that field verification remains necessary to validate conditions that may not be reflected in available datasets. Future implementations could increase robustness by incorporating data-quality indicators, explicitly identifying missing information, or supporting human-in-the-loop validation procedures.

Several limitations should be acknowledged. First, the study was conducted in collaboration with a single utility contractor and focused specifically on low-voltage reinforcement projects. Although the design process involved both engineers and construction managers, organisational practices and constructability knowledge may differ across utility providers and project contexts. Additional validation across multiple organisations would strengthen the generalisability of the identified constructability factors and assessment rules. Second, the current prototype focuses on static spatial conditions. While this aligns with its intended role in supporting early design decisions, construction activities are inherently temporal. Factors such as road-closure windows, traffic patterns, noise restrictions, and seasonal conditions may influence constructability but are not currently represented. Future work could therefore investigate integrating temporal constraints and dynamic digital-twin environments to support time-dependent constructability assessment.

Finally, the prototype primarily supports identifying constructability conflicts and risks. Although this contributes to more systematic and consistent decision-making, engineers remain responsible for evaluating trade-offs and selecting preferred design alternatives. A promising direction for future research is the development of more active decision support capabilities that not only identify conflicts but also propose alternative routes, construction methods, or mitigation strategies. The evaluation also highlighted the importance of configurable rule sets that allow assessment parameters to be adapted to different utility providers, engineering guidelines, and regulatory contexts. Together, these developments would support the transition from project-specific constructability checks to more adaptable and intelligent geospatial decision-support systems.

6. Conclusions

This paper presented a GIS-based constructability assessment prototype for low-voltage utility network design. The prototype formalises constructability knowledge into a rule-based Decision Support System that combines urban spatial data, project-specific design information, and GIS analysis to identify constructability conflicts during early design stages. An application to a real-world low-voltage reinforcement project demonstrated the ability to systematically detect hard, soft, and workflow clashes, while practitioner evaluation confirmed its usefulness in supporting consistent and transparent decision-making. The study demonstrates how geospatial data and formalised constructability knowledge can be integrated to support constructability assessment in utility design. Future research should focus on integrating SU and temporal data, improving robustness to incomplete or inaccurate datasets, and extending the system with additional constructability rules and more active decision support capabilities.

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