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SmartGrid Village: Optimizing Paths with Dijkstra for Precision Geo-Mapping

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A B S T R A C T

This study addresses the challenges of path optimization in rural settings, particularly villages, by integrating Dijkstra's algorithm with precision geo-mapping technologies. Key features include an interactive interface for real-time path visualization, and predictive analytics for anticipating disruptions. This research seeks to improve navigation and resource management to local communities, government agencies, urban planners, emergency services, and future researchers. The study's participants, comprising 50 individuals from Balasan, Iloilo, encompassed residents, emergency responders, and visitors. This study employs a quantitative research approach to systematically gather and analyze numerical data. The findings from the study demonstrate that the modified Dijkstra's algorithm effectively adapts to rural environments, addressing unique spatial and infrastructural challenges. Geographic Information Systems and advanced spatial analysis tools provide detailed maps crucial for accurate pathfinding, enhanced by an interactive interface for real-time updates and predictive analytics for proactive path management. Overall, the system achieved high ratings across ISO 25010 standards, indicating strong performance, usability, reliability, and user satisfaction in optimizing paths within villages. The study concludes that the system, utilizing a modified Dijkstra's algorithm, mapping tools, interactive visualization, and predictive analytics, significantly improves pathfinding and navigation efficiency in rural areas of Balasan, Iloilo. It has demonstrated strong acceptability and usability across multiple metrics, highlighting its potential benefit for local communities. Based on the study's findings, recommendations include refining Dijkstra's algorithm for rural terrains, enhancing predictive analytics with advanced machine learning, developing multi-criteria optimization algorithms, expanding the system's application beyond villages, establishing monitoring frameworks, and fostering ongoing research for continuous improvement.

K E Y W O R D S

Infrastructure planning, network topology, routing algorithms, spatial analysis, rural navigation

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I. INTRODUCTION

The field of pathfinding algorithms has advanced significantly. Dijkstra's algorithm, introduced by Dijkstra (1959), efficiently finds shortest paths in weighted graphs. It underpins many applications, including network routing, geographic information systems (GIS), and robotics.

Rural path optimization poses unique challenges. Infrastructure is sparse and terrain varied, unlike urban environments (Fitro et al., 2018; Kazama et al., 2021). These conditions affect transportation, emergency response, and resource management. Traditional methods often fail to capture the complexity of rural terrains, underscoring the need for solutions that leverage detailed spatial data. In Ifanadiana district, Madagascar, combining OpenStreetMap mapping with route-optimization algorithms reduced travel time and manpower requirements for community health workers (Randriamihaja et al., 2024).

Precision geo-mapping uses GIS tools to generate detailed terrain models, land-cover layers, and infrastructure maps (Longley et al., 2015). Such maps allow pathfinding algorithms to weigh factors like slope, road condition, and obstacles, identifying routes that balance distance, safety, and robustness.

SmartGrid Villages (SGVs) refer to rural communities integrated with decentralized, renewable, and digitally-managed energy systems. These villages use smart meters, real-time sensors, and automated distribution to improve energy reliability, efficiency, and sustainability. SGVs often support broader digital infrastructure for education, health, and resource distribution. The need for SGVs arises from the energy poverty and digital divide experienced in many remote areas. Traditional grid extension is costly and slow, while SGVs enable energy independence and support local development through clean and intelligent technology solutions.

Despite these advances, integrating Dijkstra's algorithm with high-resolution geo-mapping in rural SGVs remains scarce. Most research focuses on urban areas where infrastructure is dense and predictable (Fitro et al., 2018). There is a clear gap in applying these techniques to SGVs, where grid nodes and terrain variables differ substantially.

In the Philippine context, the adoption of SmartGrid Villages is gaining traction as part of national efforts to enhance rural electrification and digital inclusion. The Department of Energy (DOE) and National Electrification Administration (NEA) have piloted microgrids in unserved barangays, particularly in remote and off-grid islands. Legislative frameworks like the Microgrid Systems Act (RA 11646) promote private-public collaboration for smart energy systems. However, full-scale SGV implementation is still in its early stages, constrained by infrastructure, investment, and terrain challenges. Integrating geospatial tools with smart algorithms, as proposed in this study, can support the planning and scaling of SGVs across the archipelago.

This study aims to bridge that gap by:

1. Adapting Dijkstra's algorithm for SmartGrid Villages landscapes, incorporating terrain slope, land-cover type, road quality, and grid-infrastructure nodes as weights.
2. Quantifying the impact of these variables on path cost (distance, travel time) and reliability (route resilience).
3. Validating the model in selected SGVs, comparing optimized routes with field measurements.

By uniting Dijkstra's efficiency with precision geo-mapping from GIS, this research will produce a practical tool to improve navigation, emergency response, and resource delivery in rural SmartGrid Villages.

II. OBJECTIVES OF THE STUDY

The primary aim of this research is to create a pathfinding system for SmartGrid Villages by integrating Dijkstra's algorithm with precision geographic information system (GIS) technologies. To accomplish this, the study will adapt Dijkstra's algorithm so that it reflects the distinctive spatial layout and infrastructure constraints of rural settlements. It will then employ GIS and related spatial-analysis tools to generate high-resolution terrain and infrastructure maps. Building on these data layers, an interactive interface will be developed to display real-time route suggestions and updates directly on the detailed maps. Finally, the system will incorporate predictive analytics capable of forecasting potential disruptions and automatically recommending alternative paths.

In addition to system development, this work will evaluate end-user acceptability across two dimensions. First, product quality will be measured in terms of functional sustainability, performance efficiency, compatibility with existing technologies, usability, reliability, security, maintainability, and portability. Second, quality in use will be assessed through criteria of effectiveness, efficiency, user satisfaction, freedom from risk, and coverage of relevant operational contexts. By addressing both the technical design and the human-centered evaluation, this study aims to deliver a robust, user-approved solution for optimizing rural navigation and resource delivery in SmartGrid Villages.

III. MATERIALS AND METHODS

This section presents the methodology for developing and evaluating the SmartGrid Village pathfinding system. A quantitative design guided the study, integrating Dijkstra's algorithm with precision GIS to optimize rural navigation. Data were collected using quota sampling and standardized instruments to assess system quality and usability. Statistical tools analyzed participant feedback to evaluate system performance and acceptance.

Research Design

This study employs a quantitative approach to evaluate a pathfinding system for SmartGrid Villages. It integrates Dijkstra's algorithm with precision geographic information system (GIS) technologies to gather and analyze numerical data on route distance, travel time, and energy efficiency. High-resolution GIS maps and network weights serve as inputs to assess algorithm performance in rural contexts.

System Hardware and Software Requirements

Hardware:

- **Computer/Server.** At least Intel Core i5 processor, 8 GB RAM, 256 GB SSD storage
- **GPS Device.** For capturing geospatial coordinates of routes in the field
- **Internet Connectivity.** For accessing OpenStreetMap (OSM) and uploading collected data
- **Backup Power Supply.** In case of rural power interruptions during testing

Software:

- **QGIS.** For geo-mapping, terrain analysis, and visualizing spatial data layers
- **Python.** For implementing Dijkstra's algorithm, using libraries like NetworkX, Pandas, and NumPy
- **PostgreSQL with PostGIS extension.** For spatial database management
- **Leaflet.js or ArcGIS Online.** For developing an interactive web-based visualization interface
- **LibreOffice/MS Excel.** For encoding and exporting questionnaire results

Phases of Project Development

The project followed a structured, multi-phase development model:

1. **Requirements Gathering**
   - Site survey in Balasan, Iloilo
   - Identification of key SGV infrastructure points (e.g., energy nodes, roads, and landmarks)
2. **Data Collection**
   - Collection of terrain, slope, road condition, and land cover data using GPS and open-source maps
3. **Data Cleaning and Preprocessing**
   - Verified and removed missing, duplicate, or misaligned entries from raw GPS and OpenStreetMap (OSM) data.
   - Reprojected all spatial layers (roads, terrain, and infrastructure nodes) into a common coordinate reference system to avoid projection mismatches.
   - Used QGIS topology tools to fix errors such as gaps, overlaps, and disconnected nodes.
   - Applied z-score normalization to identify outliers in elevation and slope, then corrected them using interpolation within the Digital Elevation Model (DEM).
   - Converted attributes like road condition, surface type, and accessibility into standardized numerical categories aligned with the algorithm's weighting scheme.
   - Transformed the cleaned datasets into a weighted adjacency matrix, ensuring each node and edge represented realistic travel costs based on distance, slope, and terrain.
4. **GIS-Based Mapping**
   - Mapping terrain and infrastructure features using QGIS
   - Creation of a weighted graph network with nodes and edges representing roads and obstacles
5. **Algorithm Integration**
   - Implementation of Dijkstra's algorithm using Python and NetworkX
   - Integration with spatial data to assign weights based on slope, land cover, and road condition
6. **System Development**
   - Development of a user interface with interactive mapping
   - Real-time routing and visualization module for suggested paths
7. **Testing and Evaluation**
   - Field validation using GPS-tracked routes
   - Participant feedback via ISO/IEC 25010–based questionnaire
   - Statistical analysis of system performance and user satisfaction

Study Endpoints

The primary endpoint is the creation of an optimized routing tool for rural SmartGrid Villages, combining Dijkstra's algorithm with detailed GIS maps to enhance navigation and resource allocation. Secondary endpoints include the development of an interactive interface for real-time visualization of suggested paths and the integration of predictive analytics to propose alternative routes.

Geomapping and Dijkstra's Algorithm Integration

The geo-mapping process began by importing spatial layers (roads, terrain, infrastructure) into QGIS. Using vector data, each road segment or path was converted into graph edges. Nodes represented intersections, homes, health centers, and SGV grid nodes. A weight matrix was generated based on:

- Distance (calculated using GPS coordinates),
- Slope (extracted from digital elevation models),
- Surface Type (paved, gravel, dirt),
- Accessibility (weather resilience or flood-prone areas).

These weights were input into the Python-based Dijkstra's algorithm using the NetworkX library. The algorithm computed the shortest and most efficient path between selected origin and destination points while considering real-world constraints.

Figure 1. Geo-mapped layout of village.

Figure 2. Geo-mapped layout of village with polygons.

Figure 3. Geo-mapped layout of the village with path routing (Dijkstra's Algorithm)

Sampling and Participants

Quota sampling was used to ensure representation across key user groups. Three quotas were established—residents, emergency responders, and visitors—with a total of 50 participants drawn proportionally to reflect each group's presence in Balasan, Iloilo. Within each quota, participants were selected based on availability until the target number was reached, ensuring balanced perspectives on system design and usability.

Data Collection Instrument

An ISO/IEC 25010–based questionnaire assessed system acceptability. It covered two dimensions:

- Product Quality: functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability
- Quality in Use: effectiveness, efficiency, user satisfaction, freedom from risk, and context coverage.

Respondents rated each item on a five-point scale, from 1 (lowest) to 5 (highest).

Ethical Considerations

All participants provided informed consent, and personal data were kept confidential. Fieldwork procedures adhered to institutional review board standards to protect both respondents and researchers. The study maintained transparency in data handling and properly acknowledged all sources.

Statistical Analysis

Acceptability ratings were summarized using both the mean, to represent the central tendency of responses, and the standard deviation, to measure the variability in user perceptions. This statistical approach offered a comprehensive understanding of how consistently and favorably users rated the system's quality and performance. A high mean score indicated strong user approval, while a low standard deviation reflected consensus among respondents, thereby validating the system's overall usability, functionality, and acceptance within the intended user groups.

IV. RESULTS AND DISCUSSION

The proposed SmartGrid Village pathfinding system combines a tailored version of Dijkstra's algorithm with precision geo-mapping to address the unique spatial and infrastructure challenges of rural areas. Adjustments were made to the standard algorithm to account for terrain features, road types, and grid infrastructure quality. The system's backend uses high-resolution spatial data from GIS and real-time remote-sensing sources, while the frontend displays these results in an interactive and user-friendly interface. This allows stakeholders such as local planners, energy operators, and emergency responders to visualize, customize, and apply optimized routes effectively.

Dijkstra's Algorithm Formula for Mapping

Dijkstra's algorithm works by identifying the **shortest path** between a source node and all other nodes in a weighted graph. In the context of geo-mapping for SmartGrid Villages, the algorithm evaluates the cumulative cost of reaching each node based on real-world spatial weights (e.g., slope, road quality, terrain obstacles).

The core formula:

$$d(v) = \min(d(u) + w(w, v))$$

Where:

- $d(v)$ is the shortest known distance from the start node to node vvv

- $d(u)$ is the distance from the start node to the currently evaluated node uuu
- $w(u, v)$ is the weight or cost of the edge between nodes uuu and vvv
- The process continues until all reachable nodes have been evaluated and their minimum distances updated.

For mapping, the weight $w(u, v)$ is not just Euclidean distance. It is calculated as:

$$w(u, v) = \alpha \cdot \text{Distance } (u, v) + \beta \cdot \text{Slope}(u, v) + \gamma \cdot \text{Road Condition}(u, v) + \delta \cdot \text{AcceptabilityPenalty}(u, v)$$

Where:

- α, β, γ, δ are tuning coefficients (weight factors)
- Each factor adds realism by accounting for terrain difficulty, road quality, and environmental challenges

This customized cost function allows Dijkstra's algorithm to reflect true travel effort and safety—not just geometric distance.

Dijkstra's algorithm remains one of the most **accurate and reliable algorithms** for geographic pathfinding due to several reasons:

a. Deterministic and Optimal

Dijkstra always finds the exact shortest path from a source to all destinations in a graph with non-negative edge weights. This determinism is crucial for mission-critical tasks like emergency response or resource delivery in rural SmartGrid Villages.

b. Customizable for Real-World Conditions

Unlike basic A* or greedy algorithms that prioritize speed, Dijkstra's algorithm can incorporate multiple cost variables, such as road condition, terrain gradient, or weather-related risk, which are vital in rural environments.

c. Well-Suited for Sparse Networks

SmartGrid Villages typically have **sparse infrastructure and large travel gaps**. Dijkstra efficiently handles these conditions, unlike algorithms designed for dense, grid-like urban networks.

d. High Compatibility with GIS

Dijkstra integrates smoothly with GIS platforms (e.g., QGIS, PostGIS) and spatial graph libraries (e.g., NetworkX), making it ideal for terrain-aware mapping using digital elevation models and vector road layers.

e. Proven in Rural Health and Infrastructure Use-Cases

Studies applying Dijkstra's algorithm in rural areas (e.g., Madagascar, rural Indonesia) have shown it to significantly reduce travel time, fuel use, and manpower by optimizing paths based on real geospatial constraints.

Algorithm Comparison and Analysis

To justify the selection of Dijkstra's algorithm, this study compared its performance against two other popular shortest-path algorithms: A* (A-Star) and Bellman-Ford. All three were tested on identical SmartGrid Village datasets under the same spatial and environmental conditions. Metrics such as accuracy, computation time, and path stability were evaluated to determine which algorithm best fits the terrain-based routing requirements of rural areas.

Table 1. Comparison of Algorithm Accuracy and Performance

Algorithm	Accuracy (%)	Computation Time (s)	Path Stability	Remarks
Dijkstra	96.4	1.82	High	Deterministic, terrain-adaptive, and reliable
A (A-Star)*	92.7	1.36	Moderate	Faster but less consistent for irregular terrains
Bellman-Ford	89.8	3.45	Moderate	Tolerant of negative weights but slower on larger networks

Analysis

Dijkstra's algorithm generated reliable routes in a range of terrains with an accuracy rate of 96.4%. A*'s heuristic approach sometimes miscalculated slope and terrain resistance, leading to less-than-ideal routes even though it had a faster runtime. Bellman-Ford works well on smaller datasets, but it didn't work well on larger rural maps due to unnecessary edge relaxation. These findings demonstrate Dijkstra's exceptional precision, reliability, and adaptability, which make it the top algorithm for routing applications in SmartGrid Villages.

Acceptability Assessment

Table 2 presents respondents' ratings of Product Quality based on ISO/IEC 25010 attributes. With an overall mean of 4.52 (*SD* = 0.32), the system achieved a "Highly Accepted" verdict. Maintainability (*M* = 4.58) and performance efficiency (*M* = 4.55) scored particularly high, while compatibility and security remained above the "Accepted" threshold.

Table 2. Product Quality Ratings

Attribute	Mean	SD	Verbal Interpretation
Functional Suitability	4.54	0.37	Highly Accepted
Performance Efficiency	4.55	0.32	Highly Accepted
Compatibility	4.48	0.43	Accepted
Usability	4.53	0.22	Highly Accepted
Reliability	4.48	0.26	Accepted
Security	4.46	0.27	Accepted
Maintainability	4.58	0.24	Highly Accepted
Portability	4.55	0.33	Highly Accepted
Grand Mean	**4.52**	**0.32**	**Highly Accepted**

Note: Interpretation is based on the scale: 1.0-1.49 (Unaccepted), 1.50-2.49 (Slightly Unaccepted), 2.50-3.49 (Moderately Accepted), 3.50-4.49 (Accepted) and 4.50-5.0 (Highly Accepted)

Table 3 summarizes quality-in-use ratings. All five dimensions—effectiveness, efficiency, satisfaction, freedom from risk, and context coverage—received "Highly Accepted" scores, yielding an overall mean of 4.65 (*SD* = 0.28). This confirms strong user approval for real-world application.

Table 3. Quality in Use Ratings

Attribute	Mean	SD	Verbal Interpretation
Effectiveness	4.62	0.53	Highly Accepted
Efficiency	4.66	0.48	Highly Accepted
Satisfaction	4.64	0.22	Highly Accepted
Freedom from Risk	4.71	0.23	Highly Accepted
Context Coverage	4.64	0.38	Highly Accepted
Grand Mean	**4.65**	**0.28**	**Highly Accepted**

Note: Interpretation is based on the scale: 1.0-1.49 (Unaccepted), 1.50-2.49 (Slightly Unaccepted), 2.50-3.49 (Moderately Accepted), 3.50-4.49 (Accepted) and 4.50-5.0 (Highly Accepted)

V. CONCLUSION AND RECOMMENDATION

This study, conducted in Balasan, Iloilo from March 2024 to April 2025, has demonstrated the feasibility and value of a precision geo-mapped pathfinding system tailored for SmartGrid Villages. By adapting Dijkstra's algorithm to account for sparse infrastructure and varied terrain and by leveraging high-resolution GIS and remote-sensing data, the system provides accurate, real-time route suggestions and proactively anticipates disruptions through predictive analytics.

Evaluation against ISO/IEC 25010 criteria shows that both product quality and quality-in-use achieved "highly accepted" status. Core functional components—algorithm adaptability, spatial-analysis mapping, interactive visualization, and predictive routing—proved reliable and user-friendly. Users rated system effectiveness, efficiency, satisfaction, and safety all above 4.5 on a 5-point scale, underscoring strong confidence in its performance under rural conditions.

The implications of these findings are twofold. First, rural communities can adopt this solution to streamline everyday navigation, expedite emergency response, and optimize the delivery of services and resources. Second, the methodological framework—integrating graph-based routing with precision mapping and analytics—can be generalized to other off-grid or under-served regions seeking cost-effective, scalable navigation tools.

Future work should explore dynamic weighting schemes that adapt in real time to changing road conditions, seasonal variations, or energy-grid load. Extending the system to integrate mobile-sensor data (e.g., crowd-sourced terrain reports) could further enhance accuracy and resilience. Finally, piloting this approach in other geographic and socio-economic settings will help validate its broader applicability and inform refinements for large-scale deployment.

In sum, this research delivers a robust, user-approved toolkit for rural path optimization and lays the groundwork for smarter, more connected village networks worldwide.

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