United International Journal of Multidisciplinary Research (UIJMR)
An International Peer-Reviewed and Refereed Multidisciplinary Journal
ISSN: 3048-6726 www.uijmr.in Impact Factor: 6.934 (SJIF) Vol-3,Issue-2 ;April, May & June),2026

Neutrosophic M-Group Approach for Network Reliability Analysis under Uncertainty

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Article Received:12-03-2025 Article Modified:13-04-2026
Article Accepted:17-04-2026 Article Published:18-04-2026
DOI:10.37854/UIJMR.2026.3.2.42

Abstract
Network reliability evaluation is an essential component of modern communication, IoT, and sensor infrastructures. Classical reliability models cannot effectively represent uncertain, incomplete, and contradictory information arising from link failures, fluctuating loads, and unpredictable environmental influences. Neutrosophic sets for modeling network reliability, where network paths form a neutrosophic algebraic structure influenced by the external operators representing load variations, temperature, interference, attacks, and maintenance actions. The proposed model captures both the changes in structural connectivity and the uncertainty, induced by the conditions of the operators. A numerical case study is presented based on a 4-node communication network. The results indicate that the Neutrosophic M-Group framework offers a richer reliability analysis compared to the classical, fuzzy, and probabilistic models.

1. Introduction

Reliability of computer networks, sensor systems, and communication infrastructures recently became a very active research area because of rapid technological growth and increasing demand for seamless services. The traditional reliability approaches-probabilistic models, fault trees, Markov chains-assume crisp or probabilistic behavior. However, real-world networks include:

(i) Partial observations (missing sensor data),
(ii) Conflicting reliability reports (hardware logs vs. software logs),
(iii) Dynamic environmental conditions (heat, load, electromagnetic interference),
(iv) Cyber-attacks or congestion,

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all of which generate indeterminacy and non-linear uncertainty.

Smarandache's neutrosophic theory is a generalisation of fuzzy and intuitionistic fuzzy logic through the separation of truth, T, indeterminacy, I, and falsity, F, which enables modeling: Known reliability (T), Unknown factors (I), Failure likelihood (F), without restrictingT+ I+ F= 1.

Classical M-groups (groups with operators) provide an algebraic structure in which group elements experience transformations determined by external operators. When extended to neutrosophic environments, M-groups become powerful tools for modeling network components under varying environmental or operational conditions. A Neutrosophic M-Group Model is proposed in this paper for the evaluation of network reliability.

2. Preliminaries

This section introduces the fundamental concepts of neutrosophic sets, M-groups, and classical network reliability. These ideas aid in simulating structural behaviour, dynamic processes, and unpredictability in real-world networks. They serve as the foundation for creating a framework for generalised neutrosophic reliability.

2.1 Neutrosophic Set

Neutrosophic membership of any element, x, is represented as

$$x = \langle T(x), I(x), F(x) \rangle, T, I, F \subseteq [0,1],$$

with no constraint on their sum.

2.2 Classical M-Group

Let G be a group and M be set of operators. Then G is called an M-group, if $m(ab) = (ma)(mb), \forall m \in M, a, b \in G.$

Example:

Consider the set G = {0, 1, 2, 3} and define the operation * as addition modulo 4 (denoted by +). The addition table for this set is:

*	0	1	2	3
0	0	1	2	3
1	1	2	3	0
2	2	3	0	1
3	3	1	0	2

Here, the identity element e is 0 since a + 0 = 0 + a = a for all a in G.

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Now, let's check the m-property for each element in G:
1. For a = 0, there exists b = 0 such that 0 + 0 = 0 + 0 = 0 (using the identity element).
2. For a = 1, there exists b = 3 such that 1 + 3 = 3 + 1 = 0 (using the identity element).
3. For a = 2, there exists b = 2 such that 2 + 2 = 2 + 2 = 0 (using the identity element).
4. For a = 3, there exists b = 1 such that 3 + 1 = 1 + 3 = 0 (using the identity element).

Since each element in G has an element that satisfies the m-property, this set G with the operation * (addition modulo 4) would be an example of an m-group.

2.3 Network Reliability

Network nodes and edges define paths. Reliability of series/parallel edges is traditionally computed using probability. But real networks have: (i) Uncertain link qualities,
(ii) Conflicting sensor readings,
(iii) Changing conditions → operators.

This motivates Neutrosophic generalization.

3. Neutrosophic M-Group

Let (G) be a group representing network paths under concatenation.
The Neutrosophic M-Group is

$$N(G) = \{\langle g, T(g), I(g), F(g)\rangle : g \in G\}$$

with group operation

$$x * y = \langle ab, T(a) * T(b), I(a) \oplus I(b), F(a) \otimes F(b)\rangle,$$

where: (i) * is a t-norm (e.g., multiplication),
(ii) $\oplus$ is indeterminacy aggregation (probabilistic sum),
(iii) $\otimes$ is a t-conorm.

External operators (m \in M) model conditions such as:
(i) Increased traffic,
(ii) Temperature rise,
(iii) Hardware degradation,
(iv) Attack attempts,
(v) Maintenance activities.

The operator action is:

$$m(x) = \langle m(g), T_m(g), I_m(g), F_m(g)\rangle,$$

satisfying the M-group condition:

$$m(x * y) = m(x) * m(y).$$

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4. Neutrosophic Modelling of Network Reliability

This model studies how reliable a communication network is when uncertainity exists.

4.1 Network Representation

Given a network N = (V,E), each edge e in E is represented neutrosophically:

$$R(e) = \langle T_e, I_e, F_e \rangle.$$

Paths combine edges through the neutrosophic group operation.

4.2 Operators Affecting Reliability

$$M = \{m_1, m_2, m_3\}$$

represent:

(i) m_1: Load increase (reduces T, increases I and F),
(ii) m_2: Maintenance (increases T, reduces F),
(iii) m_3: Attack event (sharp increase in F).

Example mappings:

$T_{m_1}(x) = 0.9T(x), I_{m_1}(x) = 1.2I(x), F_{m_1}(x) = 1.3F(x)$

Operators can be applied sequentially.

The resulting behaviour forms a Neutrosophic M-Group.

5. Neutrosophic M-Group — Detailed Numerical Case Study (Network Reliability)

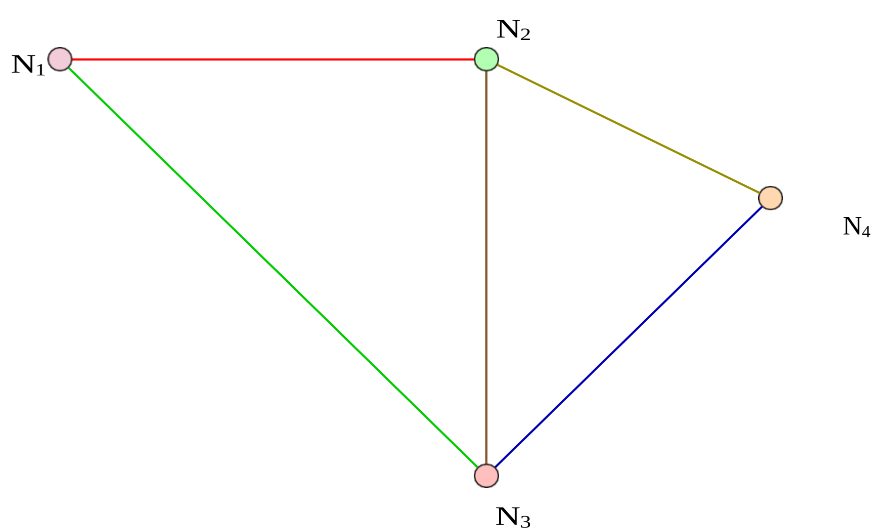

Fig. 5.1 4 - Node Network Diagram

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Network topology & edge Neutrosophic reliabilities:

Nodes: N_1, N_2, N_3, N_4.

Edges considered:

i) e_{12}: $N_1 \to N_2$
ii) e_{13}: $N_1 \to N_3$
iii) e_{23}: $N_2 \to N_3$
iv) e_{24}: $N_2 \to N_4$
v) e_{34}: $N_3 \to N_4$

Each edge (e) has a Neutrosophic reliability triple $R(e) = \langle T, I, F \rangle$. (truth = success probability, indeterminacy, falsity = failure probability.

5.1 Edge Neutrosophic Reliability

Edge	T	I	F
e_{12}	0.90	0.05	0.10
e_{13}	0.85	0.07	0.12
e_{23}	0.80	0.10	0.20
e_{24}	0.75	0.15	0.25
e_{34}	0.70	0.20	0.30

These are example numbers chosen to show different reliability/uncertainty levels.

5.2 Path Set Formation

Path set (from N_1 to N_4)

We analyze three candidate paths:

$$P_1 : N_1 \to N_2 \to N_4 (edges \quad e_{12}, \quad e_{24})$$

$$P_2 : N_1 \to N_3 \to N_4 (edges \quad e_{13}, \quad e_{34})$$

$$P_3 : N_1 \to N_2 \to N_3 \to N_4 (edges\, e_{12,} \quad e_{23}, \quad e_{34})$$

5.3 Neutrosophic Path Composition Rules

Composition rules (used consistently)

- T (truth) aggregated by multiplication (t-norm): $T_{ab}=T_a . T_b$
- I (indeterminacy) aggregated by probabilistic sum: $I_{ab}=I_a+I_b - I_a I_b$
- F (falsity) aggregated similarly by probabilistic sum: $F_{ab}=F_a+F_b - F_a F_b$

Step 1 - Baseline path Neutrosophic reliabilities (no operators):

Path P_1:

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$$Path \quad P_1 = e_{12} * e_{24}$$
$$T_{P1} = 0.90 \times 0.75 = 0.675.$$
$$I_{P1} = 0.05 + 0.15 - 0.05 \times 0.15 = 0.05 + 0.15 - 0.0075 = 0.1925.$$
$$F_{P1} - 0.10 + 0.25 - 0.10 \times 0.25 = 0.10 + 0.25 - 0.025 = 0.325.$$
$$So, R(P_1) = \langle 0.675, 0.1925, 0.325 \rangle.$$

Path P_2:

$$Path \quad P_2 = e_{13} * e_{34}$$
$$T_{P2} = 0.85 \times 0.70 = 0.595.$$
$$I_{P2} = 0.07 + 0.20 - 0.07 \times 0.20 = 0.07 + 0.20 - 0.014 = 0.256.$$
$$F_{P2} = 0.12 + 0.30 - 0.12 \times 0.30 = 0.12 + 0.30 - 0.036 = 0.384.$$
$$So, R(P_2) = \langle 0.595, 0.256, 0.384 \rangle.$$

Path P_3:

$$Path \quad P_3 = e_{12} * e_{23} * e_{34}$$
$$First\ combine \quad e_{12} \quad and \quad e_{23}:$$
$$T_{12-23} = 0.90 \times 0.80 = 0.72$$
$$I_{12-23} = 0.05 + 0.10 - 0.05 \times 0.10 = 0.05 + 0.10 - 0.005 = 0.145$$
$$F_{12-23} = 0.10 + 0.20 - 0.10 \times 0.20 = 0.10 + 0.20 - 0.02 = 0.28.$$
$$Now combine \quad with \quad e_{34}$$
$$T_{P3} = 0.72 \times 0.70 = 0.504.$$
$$I_{P3} = 0.145 + 0.20 - 0.145 \times 0.20 = 0.145 + 0.20 - 0.029 = 0.316.$$
$$F_{P3} = 0.28 + 0.30 - 0.28 \times 0.30 = 0.28 + 0.30 - 0.084 = 0.496.$$
$$So, R(P_3) = \langle 0.504, 0.316, 0.496 \rangle.$$

Step 2 - Composite reliability index for ranking:

To rank paths we define a simple composite reliability index (one choice among many):

$$\text{Re}\,liability\ Index \quad R_{idx}(P) = T_P \times (1 - I_P) \times (1 - F_P)$$

This rewards high truth and penalizes indeterminacy and falsity. (Use other multi-criteria combination if desired.)

Baseline R_{idx} values (computed stepwise)

Path P_1

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$1-I_{P1}=1-0.1925=0.8075.$

$1-F_{P1}=1-0.325=0.675.$

$R_{idx}(P_1)=0.675\times0.8075\times0.675.$

$0.675\times0.675=0.455625.$

$0.455625\times0.8075=0.3679171875\approx0.36791719.$

Path P_2

$1-I_{P2}=1-0.256=0.744.$

$1-F_{P2}=1-0.384=0.616.$

$R_{idx}(P_2)=0.595\times0.744\times0.616.$

$0.595\times0.616=0.458304.$

$0.458304\times0.595=0.27269088\approx0.27269088.$

Path P_3

$1-I_{P3}=0.684.$

$1-F_{P3}=0.504.$

$R_{idx}(P_3)=0.504\times0.684\times0.504.$

$0.504\times0.504=0.254016.$

$0.254016\times0.684\approx0.173746944.$

Baseline ranking (best → worst):

Path	Index
P_1	0.3679
P_2	0.2727
P_3	0.1737

$P_1(0.3679)>P_2(0.2727)>P_3(0.1737).$

Best Path $P_1:N_1\rightarrow N_2\rightarrow N_4$

Interpretation: P_1 is the best choice initially: highest T and moderate I/F.

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Step 3 - M-Operators Affecting Reliability:

We test three operators (typical network events). Each operator multiplies the path-level T, I, F by given factors (and then clip to ≤1 if needed). These are simple linear operator-maps for illustration.

1. Load increase - m_{load}

$$T \mapsto 0.85 \times T (\deg rades\, success)$$
$$I \mapsto 1.20 \times I (increases\, in\, \det er \min\, acy)$$
$$F \mapsto 1.25 \times F (increase\ failure)$$

2. Maintenance - m_{maint}

$$T \mapsto \min(1, 1.10 \times T)(improves T)$$
$$I \mapsto 0.80 \times I (reduces\, in\, \det er \min\, acy)$$
$$F \mapsto 0.70 \times F (reduce\ failure)$$

3. Attack event - m_{attack}

$$T \mapsto 0.75 \times T$$
$$I \mapsto 1.30 \times I$$
$$F \mapsto 1.50 \times F (cap\, at\, 1 \quad if \quad exceeds \quad 1)$$

We apply these per-path (operators act on path-level neutrosophic triples), which obeys the M-group notion m(x*y)=m(x)*m(y) because here the operator acts multiplicatively on components.

Neutrosophic M Group Concept:

Operators satisfy

$$m(x * y) = m(x) * m(y).$$

applying operator on fast reliability equals applying it on each edge then combining.

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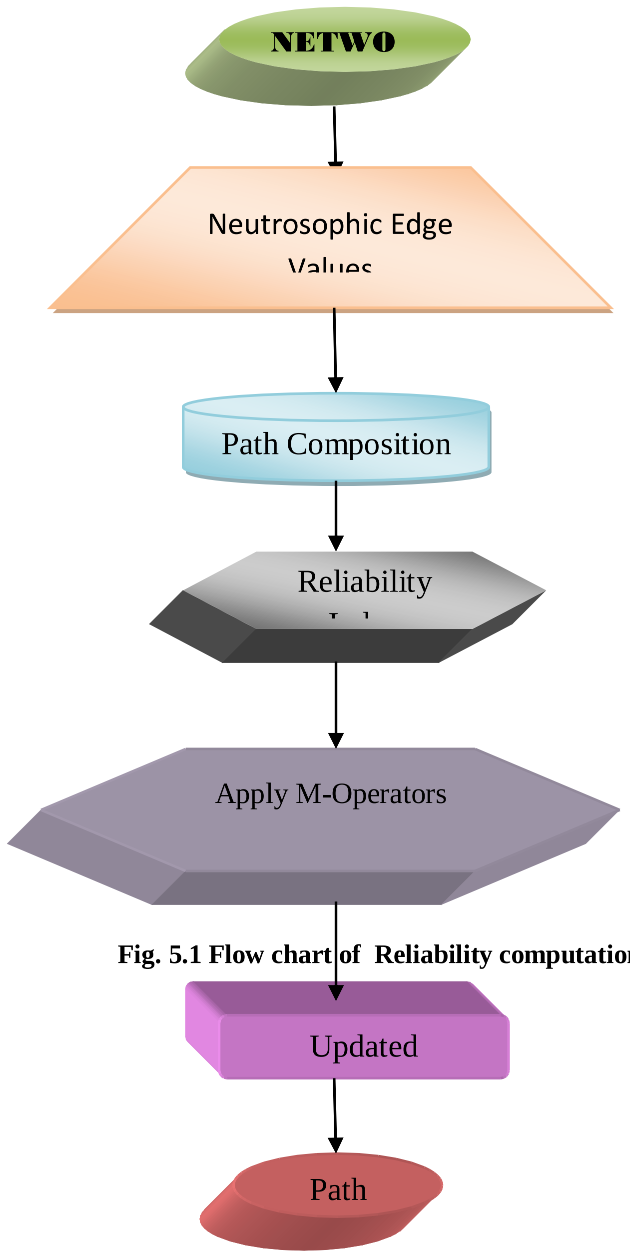

Fig. 5.1 Flow chart of Reliability computation

Step 4 - Effects of M Operators — Numerical Results

We show the Neutrosophic triples after each operator for each path, then the recomputed R_{idx}.

A. Path P_1 baseline: < 0.675,0.1925, 0.325>.

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- Under m_{load}:

$$T = 0.85 \times 0.675 = 0.57375.$$
$$I = 1.20 + 0.1925 = 0.231.$$
$$F = 1.25 \times 0.325 = 0.40625.$$
$$1 - I = 0.769, 1 - F = 0.59375.$$
$$R_{idx} = 0.57375 \times 0.769 \times 0.59375 \approx 0.2622933984.$$

- Under m_{maint}:

$$T = 1.10 \times 0.675 = 0.7425 (\le 1, so \quad unchanged).$$
$$I = 0.80 \times 0.1925 = 0.154.$$
$$F = 0.70 \times 0.325 = 0.2275.$$
$$1 - I = 0.846, 1 - F = 0.7725.$$
$$R_{idx} = 0.7425 \times 0.846 \times 0.7725 \approx 0.4852497375.$$

- Under m_{attack}:

$$T = 0.75 \times 0.675 = 0.50625$$
$$I = 1.30 \times 0.1925 = 0.25025.$$
$$F = 1.50 \times 0.325 = 0.4875.$$
$$1 - I = 0.74975, 1 - F = 0.5125.$$
$$R_{idx} = 0.50625 \times 0.74975 \times 0.5125 \approx 0.1945249805.$$

B. Path P_2 baseline: <0.595,0.256,0.384>

- Under m_{load}:

$$T = 0.85 \times 0.595 = 0.50575.$$
$$I = 1.20 \times 0.256 = 0.3072.$$
$$F = 1.25 \times 0.384 = 0.48.$$
$$1 - I = 0.6928, 1 - F = 0.52.$$
$$R_{idx} = 0.50575 \times 0.6928 \times 0.52 \approx 0.182199472.$$

- Under m_{maint}:

$T = 1.10 \times 0.595 = 0.6545.$

$I = 0.80 \times 0.256 = 0.2048.$

$F = 0.70 \times 0.384 = 0.2688.$

$1 - I = 0.7952, 1 - F = 0.7312.$

$R_{idx} = 0.6545 \times 0.7952 \times 0.7312 \approx 0.3805591821.$

- Under m_{attack}:

  $T = 0.75 \times 0.595 = 0.44625$

  $I = 1.30 \times 0.256 = 0.3328.$

  $F = 1.50 \times 0.384 = 0.576.$

  $1 - I = 0.6672, 1 - F = 0.424.$

  $R_{idx} = 0.44625 \times 0.6672 \times 0.424 \approx 0.126240912.$

C. Path P_3 baseline: < 0.504, 0.316, 0.496>

- Under m_{load}:

  $T = 0.85 \times 0.504 = 0.4284.$

  $I = 1.20 \times 0.316 = 0.3792.$

  $F = 1.25 \times 0.496 = 0.62.$

  $1 - I = 0.6208, 1 - F = 0.38.$

  $R_{idx} = 0.4284 \times 0.6208 \times 0.38 \approx 0.1010612736.$

- Under m_{maint}:

  $T = 1.10 \times 0.504 = 0.5544.$

  $I = 0.80 \times 0.316 = 0.2528.$

  $F = 0.70 \times 0.496 = 0.3472.$

  $1 - I = 0.7472, 1 - F = 0.6528.$

  $R_{idx} = 0.5544 \times 0.7472 \times 0.6528 \approx 0.2704208855.$

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- Under m_{attack}:

  $T = 0.75 \times 0.504 = 0.378$

  $I = 1.30 \times 0.316 = 0.4108.$

  $F = 1.50 \times 0.496 = 0.744(still < 1).$

  $1 - I = 0.5892, 1 - F = 0.256.$

  $R_{idx} = 0.378 \times 0.5892 \times 0.256 \approx 0.0570157056.$

6. Summary table — key numbers

Path	Baseline (T,I,F)	Baseline R_{idx}	R_{idx} under load	under maintenance	under attack
P_1	(0.675,0.1925, 0.325)	0.36791719	0.26229340	0.48524974	0.19452498
P_2	(0.595,0.256,0.384)	0.27269088	0.18219947	0.38055918	0.12624091
P_3	(0.504,0.316,0.496)	0.17374694	0.10106127	0.27042089	0.05701571

7. Interpretation & insights

Best path baseline: P_1 (highest (R_{idx}). Intuition: P_1 uses two relatively strong edges (0.90 and 0.75) and has lower combined indeterminacy/falsity than the 3-hop P_3.
Effect of maintenance: Maintenance yields substantial improvement for all paths (largest absolute gain for P_1 but all improve). Maintenance can flip marginal decisions — but here ranking remains $P_1 > P_2 > P_3$
Effect of load increase / attack: Both degrade reliability across all paths. Attacks hurt more than plain load (because they multiply F by larger factor). Under attack, absolute index values fall strongly; still P_1 remains best in our numbers.
The longer path penalty in P3 is most affected by composition: both T decrease multiplicatively, and I/F accumulate. Observe the algebraic effect of more hops here, classical in reliability, now visible in neutrosophic triple.
Edge criticality : Edge e_{34} has comparatively poor T and higher I/F (0.70,0.20,0.30) — it appears in P_2 and P_3, dragging them down. Upgrading e_{34} (or reducing its F/I) would likely help overall network reliability more than modest upgrades elsewhere.

8. Discussion

The new Neutrosophic M-Group framework developed in this study provides a powerful algebraic tool to model dynamic uncertainty in network reliability assessment. Unlike

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traditional probabilistic models that rely on crisp or single-valued reliability metrics, neutrosophic sets represent reliability in three independent dimensions: truth (T), indeterminacy (I), and falsity (F). They allow modeling of incomplete, inconsistent, or conflicting information that arises often in modern communication systems where sensor reports, logs, and environmental factors do not always align.

M-group operators allow representation of real-time influences: load fluctuations, temperature variations, interference, cyber-attacks, and maintenance activities. Each of the operators transforms neutrosophic reliability values by keeping their group structure. This operator-based flexibility makes the model suited for: dynamic networks (IoT, sensor networks),

1. mission-critical infrastructures,
2. cloud and distributed computing systems,
3. environments with unpredictable traffic and interference.

The numerical case study showed that operator-induced conditions largely alter the path reliability. High-load and attack operators decreased overall reliability while increasing indeterminacy, and maintenance increased reliability. Realistic behaviors in light of the Neutrosophic M-Group represent complicated system dynamics that cannot be captured by the classical, fuzzy, and intuitionistic fuzzy models.

9. Future Work

Several extensions of the proposed Neutrosophic M-Group model can be explored:

1. Development of Optimization Algorithms
   - Algorithms for selecting optimal paths using neutrosophic weights.
   - Multi-objective reliability optimisation under dynamic operator effects.
2. Time-Dependent M-Operators
   - Incorporate time-varying reliability where operators evolve (e.g., load patterns, attack timelines).
   - Differential or stochastic operator models.
3. Multi-layer and Multi-Hop Networks
   - Extend the framework to multi-layer communication systems (transport, session, application layer reliability).
   - Evaluate interdependencies across layers using neutrosophic operations.
4. Integration with Machine Learning
   - Predict future operator impacts using historical data.
   - Learn operator transformation parameters from real network logs.
5. Extension to Plithogenic M-Groups

- Introduce attribute-based contradiction degrees.
- Model multi-factor uncertainty (temperature, load, interference) with Plithogenic operators.

10. Conclusion

In this paper, a new Neutrosophic M-Group model was presented for network reliability evaluation under uncertainty and dynamic changes in conditions. By incorporating neutrosophic representations together with operator-based algebra, the proposed framework expands the capabilities of classical models by accounting for ambiguity, inconsistency, and conflicting network information.

The numerical case study showed that the different operator conditions related to load, maintenance, and cyber-attacks transform network reliability and change T, I, and F values. From these results, it can be observed that the Neutrosophic M-Group approach is extremely versatile and provides more realistic valuations of network reliability under complex settings. It is mathematically rigorous, can be scaled, and captures real-time network behavior. The framework's flexibility makes it a valuable tool for analyzing modern communication systems, IoT networks, and infrastructure deemed critical. The proposed extensions will enhance its applicability and theoretical richness further.

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