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A New Architecture of Logic Gates using Neutrosophic Logic: Theoretical Modeling, Design and Simulations

A. A. Salama ^{1,*} , Arafa A. Nasef ²  and Aya A. Abd El-Khalek ³ 

¹ Department of Mathematics and Computer Science, Faculty of Science, Port Said University, Egypt.
ahmed_salama_2000@sci.psu.edu.eg.

² Department of Physics and Engineering Mathematics, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33516, Egypt. arafa.nasif@eng.kfs.edu.eg.

³ Nile Higher Institute for Engineering and Technology, Mansoura, Egypt. ayayakot94@nilehi.edu.eg.

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Abstract

Here, for the first time, we provide a new architecture of classical logic gates via neutrosophic logic, a mathematical theory of uncertainty, indeterminacy, and inconsistency. Today's classic Boolean and fuzzy logic gates struggle to model real world situations with incomplete and contradictory data. We generalize classical (AND, OR, NOT) with neutrosophic truth (T), indeterminacy (I) and falsity (F). We generalize algebraic operations of neutrosophic gates; define gate models and hardware level implementations. By comparative simulations, neutrosophic gates are shown to be almost as accurate as crisp gates under crisp inputs and significantly better than both Boolean and fuzzy gates under uncertain or noisy inputs. This architecture provides a bright direction in rock-solid logic design for next generation intelligent systems.

Keywords: Neutrosophic Logic; Logic Gates; Indeterminacy; Uncertainty Modeling; Neutrosophic AND/OR/NO; Circuit Design; Fuzzy Logic; Digital Logic Systems; Neutrosophic Algebra; Hardware Implementation.

Table 1. List of abbreviations used in this paper.

Abbreviation	Full Meaning / Description
ROC	Receiver Operating Characteristic — a statistical plot comparing the True Positive Rate (TPR) and False Positive Rate (FPR) used to assess classification performance.
AUC	Area Under the Curve — a scalar value derived from the ROC curve that measures overall classification accuracy (higher AUC → better performance).
FPGA	Field-Programmable Gate Array — a reconfigurable digital hardware platform used for real-time implementation of logic systems.
TPR	True Positive Rate — ratio of correctly identified true outputs to all actual positives.
FPR	False Positive Rate — ratio of incorrectly identified true outputs to all actual negatives.
T, I, F	Truth, Indeterminacy, and Falsehood — the three components of neutrosophic logic representing certainty, uncertainty, and falsity respectively.
ns-	Neutrosophic Prefix — denotes components, gates, or operations defined under neutrosophic logic.
MUX	Multiplexer — a digital circuit that selects one of several input signals and forwards it to the output based on control signals.
HDL	Hardware Description Language — used for modeling digital circuits (e.g., Verilog, VHDL).

 Corresponding Author: ahmed_salama_2000@sci.psu.edu.eg

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1 | Introduction

1.1 | Basic Fundamentals of Logic Gates

Logic gates are the basic functional units of digital electronic circuits, and thus form the basis of computing. Typical Boolean logic gates (AND, OR, NOT) assume binary input (0 or 1) to produce respective binary output. Logical gates function correctly in the structured, defined digital environment; however, they cannot deal with ambiguity or incompleteness of data[1].

In contrast to these traditional logic gates, use of fuzzy logic gates allows operations on values that are within the continuous value range of 0 to 1. Therefore, the method of fuzzy logic can be viewed as the operational foundation upon which to resolve uncertainty. On the other hand, traditional logic gates cannot convey or measure both directionally and dimensionally indefiniteness or inconsistency, typically encountered in real-world or physical systems.

Motivation

More advanced systems are continuously being connected to the analog world in numerous ways including sensor networks, intelligent control, and Internet of Things (IoT) applications [1, 4]. However, they also become exposed to different sources of uncertainty such as background noise, component aging, temporary faults, and inconsistent inputs. Fundamental Boolean logic is not capable of handling such types of uncertainties [2,3], while fuzzy logic can only offer a limited level of help [2, 18]. What we really want is a computational approach that sees uncertainty and contradiction as two of its primary features [6, 17, 18]. And neutrosophic logic is the one that can meet this need.

An Elementary Guide to Neutrosophic Logic

Smarandache first developed neutrosophic logic, which unsurprisingly makes a major leap in the development of logic from classical to fuzzy logic. Here, every proposition or input is marked by a triplet (T, I, F), meaning:

- $T \in [0, 1]$ is the level of truth
- $I \in [0, 1]$ is the level of indeterminacy
- $F \in [0, 1]$ is the level of falsehood.

Different from the classical logic systems, here the T, I, F are three independent components, without the necessity of adding up to 1 [7, 9, 12, 17]. This design makes it feasible for neutrosophic logic to grasp the notion of uncertainty in an articulate and subtle manner, which allows contradictions and partial truths coexist without prejudice [6, 8]. Besides these, neutrosophic also has a great number of other applications as shown in [1,7, 11, 13, 32, 34].

Contributions

In this paper we introduced a new architecture of neutrosophic logic gates. The main contributions are:

1. Formulation of Neutrosophic Logic Gates: We define neutrosophic equivalents of fundamental AND, OR, and NOT gates, providing their algebraic structure and logical behavior under uncertainty [6, 12].
2. Hardware Realization: We demonstrate circuit-level implementation using analog signal representations [16] or digital hardware via multi-rail encoding and FPGA logic [15, 19].
3. Performance Evaluation: We benchmark neutrosophic gates against classical and fuzzy gates for robustness, noisy accuracy, and computational expressiveness [3, 14].

1.2 | Boolean Logic Gate Architectures

Classical digital circuits are based on Boolean algebra, using binary variables (0/1) and deterministic operations to characterize computation [22]. These gates are physically implemented by technologies such as CMOS, TTL and ECL [20, 21], constitute the backbone of traditional computers. Even though they are operationally simple and precise, Boolean structures are limited in noisy environments subject to signal degradation [23]. Their binary nature prohibits subtle analysis of partial or ambiguous signals, limiting usefulness in contexts where signal quality is less than perfect [34].

1.3 | Fuzzy logic gates: and what they can't

Building on Zadeh's pioneering work (1965), fuzzy logic extends Boolean algebra by allowing truth values to range continuously between [0, 1]. In them membership functions stand for set membership, t-norms and t-conorms for logical operations under fuzziness [24–28]. These formalisms facilitated spectacular advances in control systems engineering [5, 28], pattern classification and approximate inference methods [26]. But fuzzy systems, at bottom, represent vagueness solely through degrees of truth. They lack explicit formal means to represent indeterminacy the state of the not yet known. This representational gap is a key bottleneck in application domains like distributed sensor networks or biological systems modeling where uncertain states are intrinsic [29–31].

2 | Neutrosophic Logic for Computational Systems

Neutrosophic logic pioneered by Smarandache [29] fills the above gaps with the representation of truth (T), indeterminacy (I), and falsity (F). It has been tested and proved to work in making decisions under conflicts [31, 34], in fusing information from multiple sensors [4], in bringing intelligence to the semantic web, and in designing fault-tolerant architectures [33, 34] and is proven to be more efficient when representing uncertainty and contradictory contexts than the traditional normal references [30,32]. Hardware implementations of the basic neutrosophic gates appear to be weak despite the significant theoretical benefits. This study concurs with the view that comprehensive design methodology and hardware realizations of neutrosophic gates are yet to be developed and convincingly demonstrated via simulations [33,34], an existing gap that this research work addresses systematically.

2.1 | Neutrosophic Logic Foundations

Definition of Neutrosophic Sets

Neutrosophic logic proposed by Florentin Smarandache is a generalization of fuzzy logic to deal with truth (T), indeterminacy (I), and falsity (F) separately. The universe of discourse for the neutrosophic set A is $U = \{x, T_A, I_A, F_A\}$, where

- $T_{A(x)} \in [0,1]$: degree to which x is **true** in set A,
- $I_{A(x)} \in [0,1]$: degree to which x is **indeterminate** in set A,
- $F_{A(x)} \in [0,1]$: degree to which x is **false** in set A,

Importantly, the values of T, I, and F are **independent**, and their sum is **not constrained** to equal 1, allowing richer modeling of incomplete, conflicting, or ambiguous information.

2.2 | Operations in Neutrosophic Algebra

Since the early ages of the field of Computer Science, scientists have been working hard to devise a standard model to guarantee a consistent way of processing information and data. Thus, the standardization of the information processing domain lead to the emergence of classical logic gates which can mainly be defined with the interrelation and treatment of logical values, that's True (T) and False (F). However, the classical

logic gates are not able to answer any uncertain queries or problems as they do not contain a third logical value to define problems or conflicts. In this regard, the neutrosophic logic and sets were invented to be utilized in the logic gates. In a neutrosophic domain the truth (T), indeterminacy (I), and falsehood (F) values all can be defined to information which may help in eliminating the confusion and contradictions. Thereby we can redefine the classical logic gates in neutrosophic logic so that we can have a much smoother and easier information processing and management by converting the languages to uncertain semantic.

A logic gate is a basic building block of a digital circuit. It is an electronic circuit with one or more inputs and one output. The output depends on the type of gate and the inputs.

In this paper we discussed about redefining classical logic gates in the context of neutrosophic sets. Neutrosophic logic deals with the notions of truth T, indeterminacy I and falsehood F. For example the information such as ‘it’s raining’ can be true, indeterminately true or false. This uncertainty semantics cannot be handled using classical three valued logic.

Digital logic has been a main stream area of research in computer applications. Incorporation of neutrosophic logic in this domain is a recent development and the work is in its infancy. For example truth, indeterminacy and falsehood can be incorporated into the equality, relation and addition operation in case of computer chip.

- **Neutrosophic AND (ns-AND):**

Given two neutrosophic inputs $A = (T_A, I_A, F_A)$ and $B = (T_B, I_B, F_B)$,

The neutrosophic conjunction is defined as: $T_{A \cap B} = \min(T_A, T_B)$, $I_{A \cap B} = \max(I_A, I_B)$, $F_{A \cap B} = \max(F_A, F_B)$

A model of a conservative logic is given that preserves ‘truth’ and accumulates ‘falsehood’ but has ‘strong truth’ inputs thereby yielding ‘indeterminacy’. We propose that this is an acceptable model of ‘truth’ for certain paradoxes and similarly restate the case against ‘strong truth’ as regards certain paradoxes and ‘truth’.

- **Neutrosophic OR (ns-OR):**

$$T_{A \cup B} = \max(T_A, T_B), \quad I_{A \cup B} = \max(I_A, I_B), \quad F_{A \cup B} = \min(F_A, F_B)$$

Beneath this optimistic behavior, one can view it as an operation which aims, under conditions of uncertainty, to maximize truth while minimizing falsehood, the best possible extraction of resources from an untamed wilderness. It is success from a hopeless, passive opinion, admitting that truth cannot be guaranteed.

- **Neutrosophic NOT (ns-NOT):**

For a single input $A = (T_A, I_A, F_A)$, the neutrosophic negation is defined as:

This formulation inverts the certainty ($T \leftrightarrow F$) while complementing indeterminacy, ensuring that ambiguity is not eliminated upon inversion.

These operations are generalizations of both Boolean and fuzzy logic, and they reduce to classical definitions when indeterminacy is zero and $T + F = 1$.

3 | Proposed Neutrosophic Gate Structures

Here we are generalizing the basic gate operations in the neutrosophic CONTEXT, allowing reasoning with truth, indeterminacy and falsity at the same time. These gates generalize their classical Boolean counterparts, expressing even more in uncertain or noisy environments.

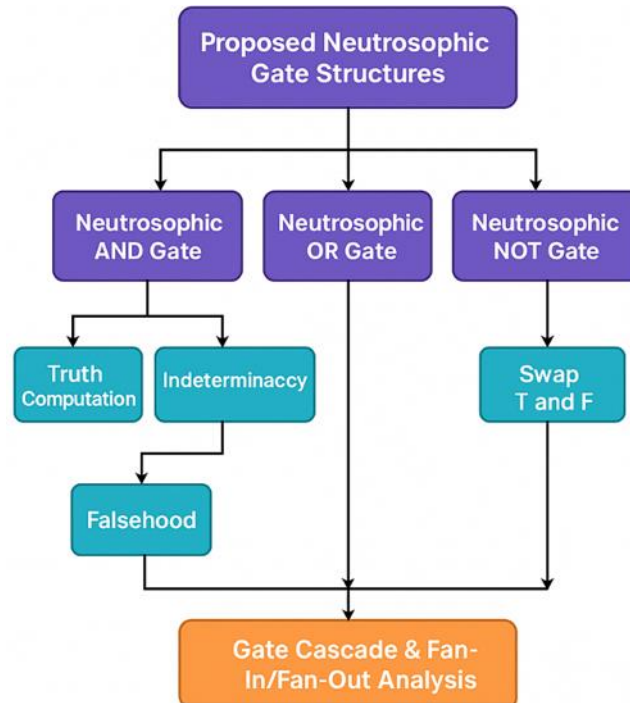


Figure 1. Flow chart of the proposed neutrosophic gates.

A Flowchart of the full design of branching structures (AND, OR and NOT) used in neutrosophic logic gates, including the functions of each gate. AND and OR gate types has three inputs each (TRUE, INDETERMINATE and FALSE) for each of its three inputs, while the NOT gate converts from FALSE back to TRUE. Each gate, when completed, feeds into the last block to be used for a final analysis of Gate Cascade and Fan-In/Fan-Out Analysis, in order to determine if they provide a properly strong signal, as well as for determining the potential scalability of each of these circuits in the future.

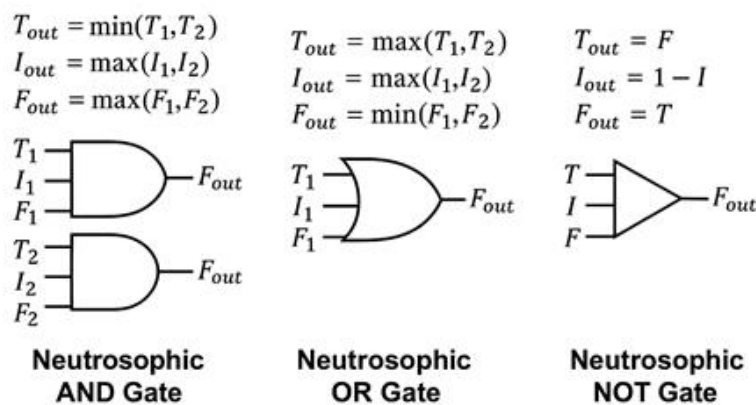


Figure 2. Proposed Neutrosophic Gate Structures.

(Neutrosophic logic gates) illustrated in Figure 2 are fundamental building blocks adapted for computing in uncertain environments. Different from traditional binary logic gates, they perform operations using the triple of truth, indeterminacy, and falsity, generate graded outputs via min/max operations, and provide an intuitive visual analogy for the new type of logic that breaks through binary constraints and models the fuzziness and contradiction in real-world information.

3.1 | Neutrosophic AND Gate

The Neutrosophic AND gate takes the regular logical AND adds a twist to deal with not-so-clear situations and stuff that's not quite black or white given two neutrosophic input signals

$$A = (T_1, I_1, F_1), B = (T_2, I_2, F_2)$$

The output triplet $(T_{out}, I_{out}, F_{out})$ is computed component-wise as:

Truth Component

$$T_{out} = \min(T_1, T_2)$$

This captures the conservative logic of AND: truth is preserved only if both inputs are strongly true.

Indeterminacy Component:

$$I_{out} = \max(I_1, I_2)$$

If either input has significant falsehood, the output increases in falsity accordingly.

Falsehood Component:

$$F_{out} = \max(F_1, F_2)$$

If either input has significant falsehood, the output increases in falsity accordingly.

Interpretation

This setup guarantees solid modeling of logical "and" situations in unclear or messy settings. The output maintains conservative truth evaluation, while indeterminacy and falsity are accumulated to avoid underestimating uncertainty.

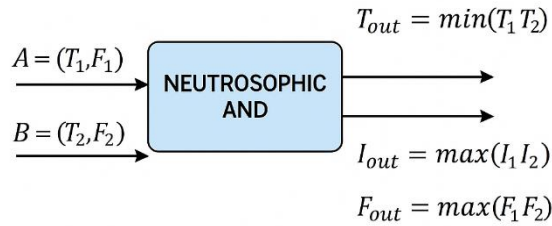


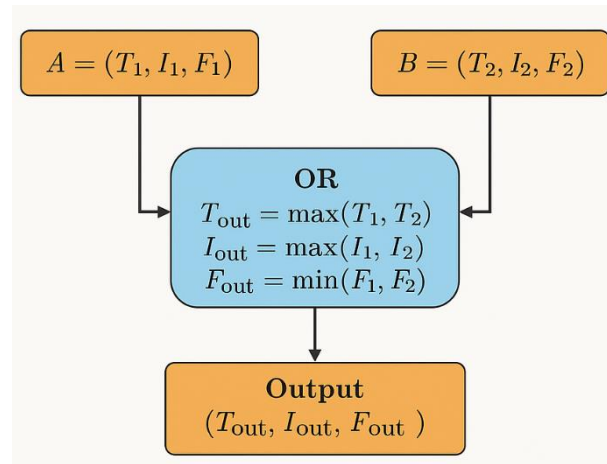
Figure 3: Neutrosophic AND Gate Structure.

Caption: This diagram shows how the Neutrosophic AND gate works, taking in two sets of numbers: $A = (T_1, I_1, F_1)$ and $B = (T_2, I_2, F_2)$. The gate computes the output components as follows:

- Truth: $T_{out} = \min(T_1, T_2)$
- Indeterminacy: $I_{out} = \max(I_1, I_2)$
- Falsehood: $F_{out} = \max(F_1, F_2)$ This design ensures that truth is confirmed only when both inputs are strongly true, while uncertainty and falsehood are conservatively preserved to reflect real-world ambiguity.

3.2 Neutrosophic OR Gate

The Neutrosophic OR gate expands the traditional OR operation by considering inputs that are uncertain or partly reliable. Imagine two neutrosophic signals: $A = (T_1, I_1, F_1)$, $B = (T_2, I_2, F_2)$. The output is a triplet: $(T_{out}, I_{out}, F_{out})$. In essence, this system maximizes truth values from the inputs, adds up their uncertainties, and minimizes falsity.



Figuer4: Neutrosophic OR Gate Structure

Figure 4 illustrates the structure of a Neutrosophic OR Gate. It operates with two neutrosophic inputs: $A = (T_1, I_1, F_1)$ and $B = (T_2, I_2, F_2)$. The gate processes these inputs using a specific set of rules:

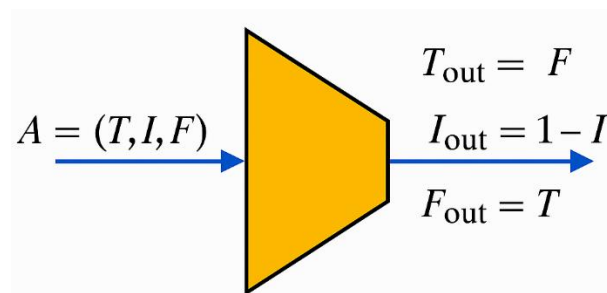
The gate handles these inputs with this logic.

- $T_{out} = \max(T_1, T_2)$
- $I_{out} = \max(I_1, I_2)$
- $F_{out} = \min(F_1, F_2)$

This approach highlights the input with the highest truth value while maintaining indeterminacy levels and minimizing falsehoods. As a result, it proves useful in decision-making systems where ambiguity or uncertainty exist.

3.3 Neutrosophic NOT Gate

The Neutrosophic NOT gate flips the input set $A = (T, I, F)$. Here's how it works: T and F swap places, causing a logical flip. The indeterminacy part is handled with care, showing reverse confidence. It maintains the idea that negation doesn't remove uncertainty, keeping things open-ended.



Figuer 5: Neutrosophic NOT Gate Structure

Imagine this: you have a neutrosophic triplet, $A = (T, I, F)$. What happens next? It gets transformed into new output components.

- $T_{out} = F$: Truth becomes falsehood

- $I_{out} = 1 - I$: Indeterminacy is inverted
- $F_{out} = T$: Falsehood becomes truth

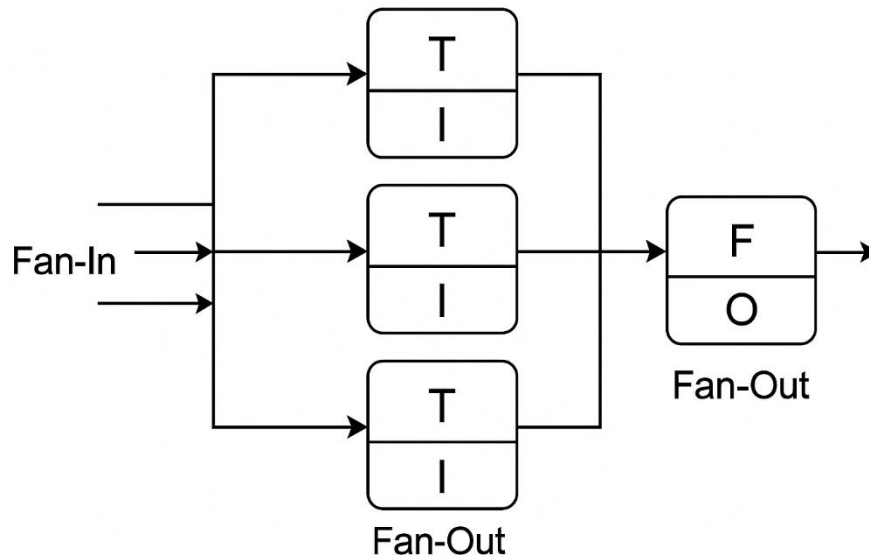
This illustrates a logical inversion process within the neutrosophic framework.

4 Analyzing Gate Cascade and Fan-in/Fan-out

In standard digital design, fan-in is the count of inputs a logic gate can handle, while fan-out is about how many gates a single gate's output can drive. However, when dealing with neutrosophic systems, cascading gates demands careful management of T (truth), I (indeterminacy), and F (falsity) propagation.

Here are some key points to consider:

- Gate Cascading: Linking multiple neutrosophic gates together leads to a crucial buildup of indeterminacy. With deeper cascades, I values tend to rise and may need normalization or threshold constraints to prevent saturation during propagation.
- Fan-in Impact: Increasing the number of inputs means the gate must manage all T, I, F values through generalized min/max operations. Without proper control via thresholds, this can cause non-linear scaling in indeterminacy.
- Fan-out Behavior: Outputs as 3-dimensional tuples necessitate caution.



Figuer6: Gate Cascade and Fan-In/Fan-Out Analysis in Neutrosophic Logic Circuits

Figure 6 illustrates how neutrosophic logic circuits manage fan-in and fan-out processes. Various inputs from multiple gates contribute to the calculation of three key elements: truth (T), indeterminacy (I), and falsehood (F). As signals pass through different gates, indeterminacy tends to accumulate, which makes normalization essential. At the output, the result from a single gate, known as a neutrosophic triplet, divides into several paths leading to other gates. This arrangement ensures that neutrosophic values remain consistent throughout the complex circuit journey.

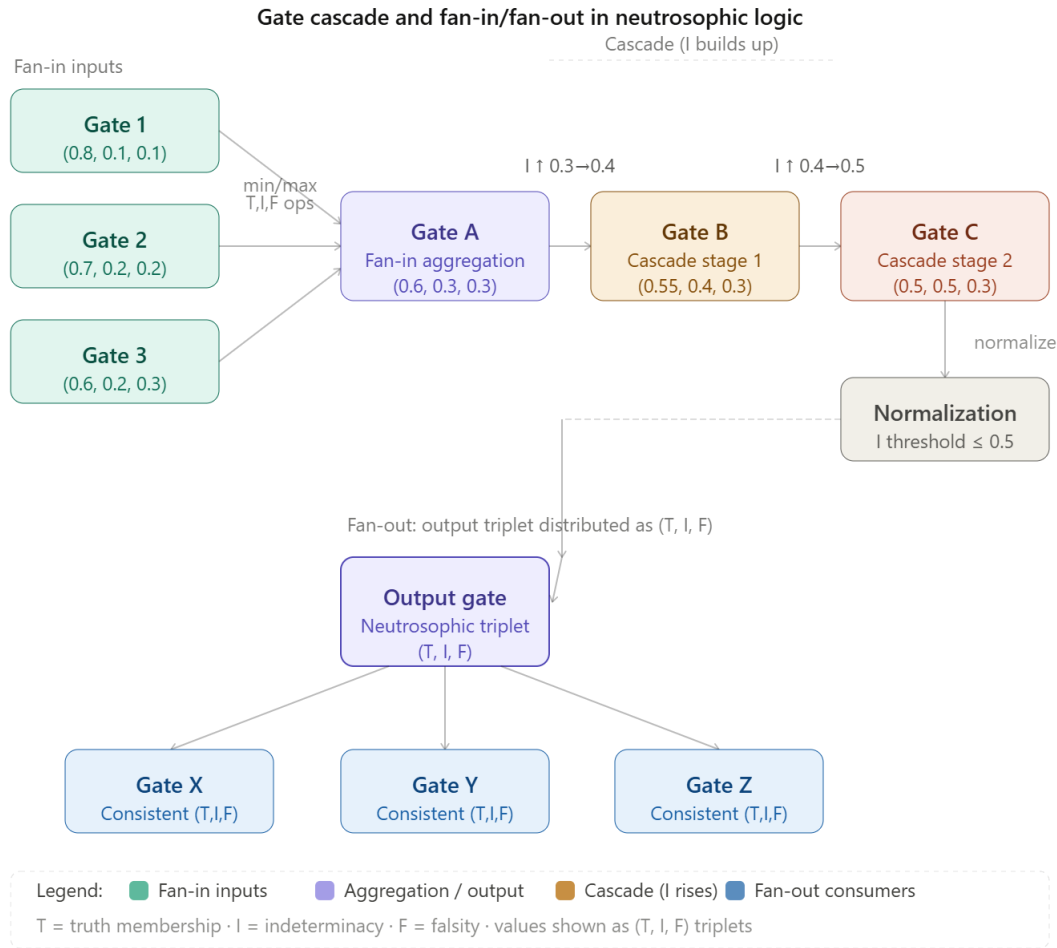


Figure 6: Analysis of Gate Cascade and Fan-In/Fan-Out in Neutrosophic Logic Circuits

This figure shows how neutrosophic logic gates handle the flow of truth (T), indeterminacy (I), and falsity (F) values through three main structural behaviors. First, on the left, you see multiple input gates bringing their neutrosophic triplets to a single aggregation gate, labeled Gate A. This process uses generalized min/max operations, revealing that more inputs lead to non-linear growth in indeterminacy.

In the middle section, the cascade traces the step-by-step progression from Gate A to B to C. Here, I values increase gradually from 0.3 to 0.4 and then to 0.5. This demonstrates how deeper gate chains can accumulate indeterminacy, making a normalization stage crucial for avoiding saturation.

Lastly, on the right side, you find the fan-out section. It shows a single output gate.

5 Implementation of Neutrosophic Logic Gates and Simulation Framework

Let's dive into how neutrosophic logic gates come to life, then explore the simulation setup assessing their capabilities. There are two routes for implementation: analog and digital. Each offers distinct ways to encode and operate components like T, I, and F.

5.1 Circuit Realization

To execute ns-AND and ns-OR operations, analog comparators and amplifiers come into play using min/max logic [16]. This approach allows for a seamless transition in signal variation.

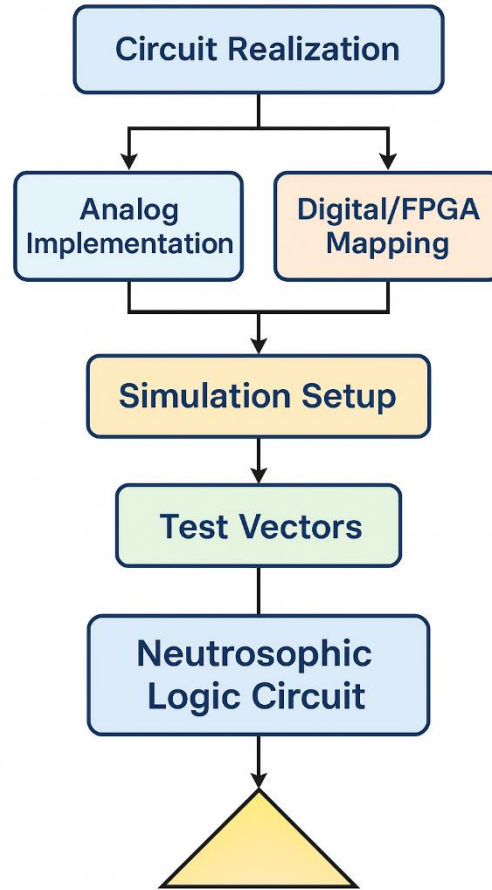
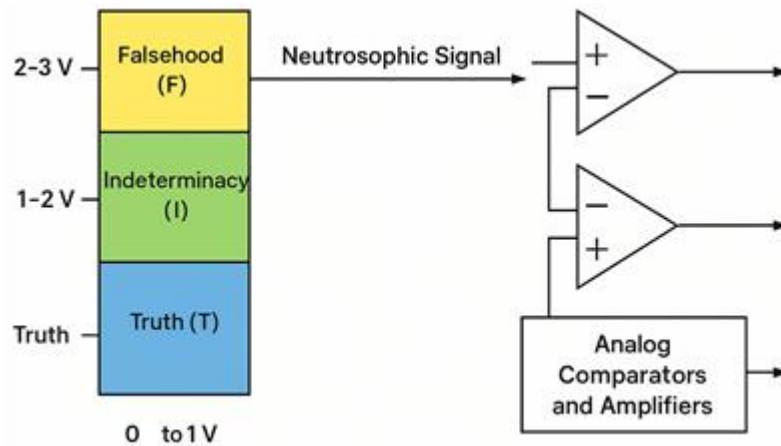


Figure 7: Circuit Realization Workflow for Neutrosophic Logic Gates

Figure 7 presents the workflow for creating circuits using neutrosophic logic gates. The process starts with two approaches: one involves analog implementation, and the other focuses on digital or FPGA mapping. These methods bring the (T, I, F) components to life in hardware. Next, simulations help check how the gates interact at a detailed level. After that, rigorous testing takes place using various test signals—sharp, ambiguous, and noisy—to assess robustness. At the end of this process, you get a validated neutrosophic circuit ready to be used in systems that handle uncertainty on a higher level.

- **Analog Implementation**

In the world of analog systems, each neutrosophic signal gets represented by three voltage levels: truth is 0–1 V, indeterminacy spans 1–2 V, and falsity covers 2–3 V. Analog comparators and amplifiers handle the essential min/max logic for ns-AND and ns-OR operations. This approach capitalizes on smooth transitions between signals. Such a method excels in environments full of uncertainty, like biomedical sensing or environmental monitoring.



Figuer.8: Analog Representation of Neutrosophic Signals via Voltage Encoding

Figure 8 presents an analog way to represent neutrosophic signals by encoding them with voltages. The figure illustrates the physical implementation of a neutrosophic signal within an analog circuit. Each part of the signal is represented by specific voltage ranges: Truth spans from 0 to 1V, Indeterminacy from 1 to 2V, and Falsehood from 2 to 3V. Analog comparators and amplifiers allow for the separate handling of these components. Circuits can thus interpret and boost neutrosophic logic signals effectively. This approach supports making decisions in situations where uncertainty is present.

- **Digital/FPGA Mapping**

In digital systems, particularly in FPGA-based designs, a triple-rail encoding is used to represent the neutrosophic triplet. Each signal is encoded in three separate binary channels one each for T, I, and F. Logical operations are realized using standard digital logic blocks configured to perform min/max operations over each channel independently. Its modular, reconfigurable, and scalable for large circuit designs.

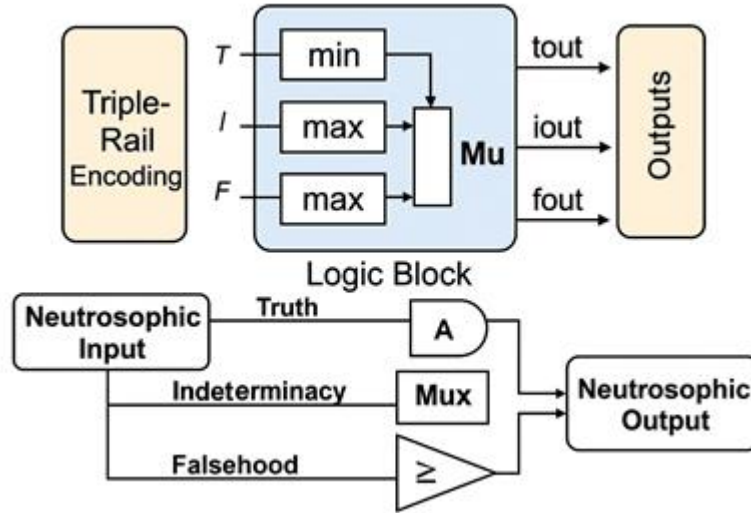


Figure 9. Digital/FPGA Implementation of Neutrosophic Logic Gates

Caption: This figure presents the **FPGA (Field-Programmable Gate Array)** implementation of neutrosophic logic gates.

The **upper block diagram** shows the **triple-rail encoding** structure, where each neutrosophic component **Truth (T)**, **Indeterminacy (I)**, and **Falsehood (F)** is processed through independent digital subcircuits consisting of *minimum (min)*, *maximum (max)*, and *multiplexer (Mux)* operations.

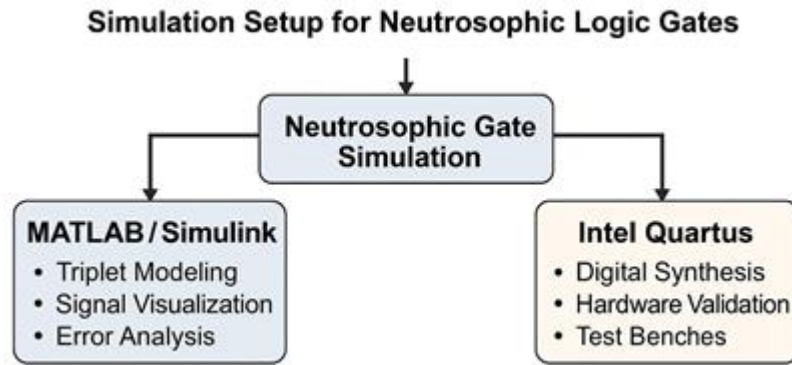
The **lower schematic** illustrates the gate-level architecture:

- **Mux (Multiplexer):** a digital selector that chooses one of multiple input signals (e.g., Truth or Indeterminacy) based on a control signal, allowing adaptive switching between logic states.
- $\geq$ and $\leq$ symbols denote *comparators* used to evaluate the relative magnitude of neutrosophic components for decision-making within the gate.

5.2 Simulation Setup

The neutrosophic gates were modeled and tested in two simulation environments:

- **MATLAB/Simulink:** Used for initial modeling of the algebraic behavior of gates with real-valued (T, I, F) inputs. This environment facilitates visualization of signal propagation and error behavior under varying degrees of noise.
- **Intel Quartus (FPGA):** Used to synthesize and test digital implementations of neutrosophic gates using Verilog HDL. This setup allows timing analysis, resource utilization assessment, and real-time waveform evaluation via test benches.



Figuer10: Simulation Setup for Neutrosophic Logic Gate

Caption: This flowchart summarizes the simulation pipeline without duplicated labels. The top block Simulation Setup branches into two paths:

- **MATLAB/Simulink** triplet (T, I, F) modeling, signal visualization, and error/uncertainty analysis.
 - **Intel Quartus / Verilog HDL** digital synthesis, resource-utilization and timing analysis, and waveform validation via test benches.
- Together, these tools provide consistent gate-level verification of neutrosophic logic designs under crisp and uncertain inputs.

5.3 Test Vectors

In order to evaluate the gate performance both in the ideal case and in the presence of uncertainty, the following test vectors were designed:

- **Crisp Inputs:** The triplets (1, 0, 0) and (0, 0, 1) were used to check the logical correctness of the gate by comparing it with the Boolean logic.
- **Uncertain Inputs:** Examples such as (0.6, 0.3, 0.1), (0.5, 0.5, 0.0), and (0.4, 0.2, 0.4) were chosen to represent the degradation of sensors, conflicting inputs, and ambiguous states, respectively.

Noisy Inputs: To simulate the real-world signal instability, random perturbations were added to the T, I, and F components.

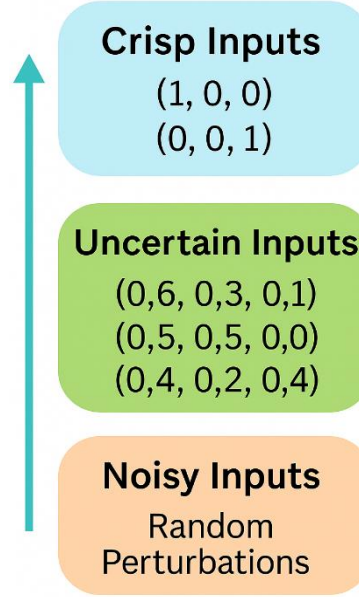


Figure 11: Test Vector Categories for

Figure 11 displays the categories of test vectors applied in assessing neutrosophic logic gate performance. It includes a variety of inputs. First, there are crisp inputs like (1, 0, 0) and (0, 0, 1), which confirm their logical equivalence to Boolean gates. Additionally, uncertain inputs such as (0.6, 0.3, 0.1) and (0.5, 0.5, 0.0) come into play; these represent ambiguous or degraded sensor signals.

6 Results and Discussion

This part reveals the findings from the simulation alongside real-world uses of the neutrosophic logic gates discussed earlier. Various input conditions underwent testing, and comparisons were made with traditional Boolean and fuzzy logic gates. The focus was on accuracy, detail, and speed during these evaluations.

6.1 Correctness Under Crisp Inputs

As a first step to check the logical correctness of the neutrosophic logic gates proposed, we tested them with crisp input triplets (1, 0, 0) representing binary 1, and (0, 0, 1) representing binary 0. Such values correspond to fully determined situations without any indeterminacy.

We tested each gate as follows:

- **Neutrosophic AND Gate:** $(1,0,0) \wedge (1,0,0)=(1,0,0)$
- **Neutrosophic OR Gate:** $(1,0,0) \vee (0,0,1)=(1,0,0)$
- **Neutrosophic NOT Gate:** $\neg(1,0,0)=(0,1,1)$

These are the **same** results as in classical Boolean logic, namely:

- $\text{AND}(1,1) = 1$

- $\text{OR}(1,0) = 1$
- $\text{NOT}(1) = 0$ (with the complement happening in T and F, and I inverted)

Since neutrosophic gates produce expected results when there is no indeterminacy, they are backwards compatible with regular digital systems. In other words, neutrosophic logic can be a super set of Boolean logic that allows for more representation capabilities but when there is no indeterminacy, the notion of correctness is preserved.

	Input	Output
AND Gate	(1, 0, 0)	(1, 0, 0)
	(1, 0, 0)	
OR Gate	(1, 0, 0)	(1, 0, 0)
	(0, 0, 1)	
NOT Gate	(1, 0, 0)	(0, 1, 1)

Figuer12: Correctness of Neutrosophic Logic Gates under Crisp Inputs

Caption: This figure depicts the logical operations of Neutrosophic AND, OR, and NOT gates when given crisp input triplets (1, 0, 0) for 1 and (0, 0, 1) for 0. The outcomes are exactly the same as classical Boolean logic, which means that the neutrosophic gates are compatible with the past. The NOT gate also shows the change of truth and false, with the indeterminate values changed around 1.

6.2 Behavior Under Indeterminate Inputs

In order to check the behavior of neutrosophic gates in such a situation, they were tested with partially indeterminate input triplets. Such inputs simulate various situations in the real world noisy sensors, missing data or even contradictory signals.

For example:

- Input A = (0.6, 0.3, 0.1)
- Input B = (0.7, 0.2, 0.2)

The result of the **Neutrosophic AND** gate is determined as

$$T_{out} = \min(0.6, 0.7) = 0.6, \quad I_{out} = \max(0.3, 0.2) = 0.3, \quad F_{out} = \max(0.1, 0.2) = 0.2 \\ \gg \text{output} = (0.6, 0.3, 0.2)$$

This version keeps the subtle distinctions of the original text very clear between the concepts of **truth**, **indeterminacy**, and **falsehood**.

For example, fuzzy logic gates, which model uncertainty with a single membership value, may produce a result like 0.55., and while this number might make sense, it does not indicate what is uncertain about the signal or whether it is being caused by conflicting sources, partial evidence, or a lack of information.

On the other hand, neutrosophic logic gates with their **tripartite representation** provide **fine-grained interpretation** and **traceability of uncertainty**, and hence can be used in all those systems where the decision is very important such as in medical diagnostics, autonomous robotics, and hybrid sensor networks.

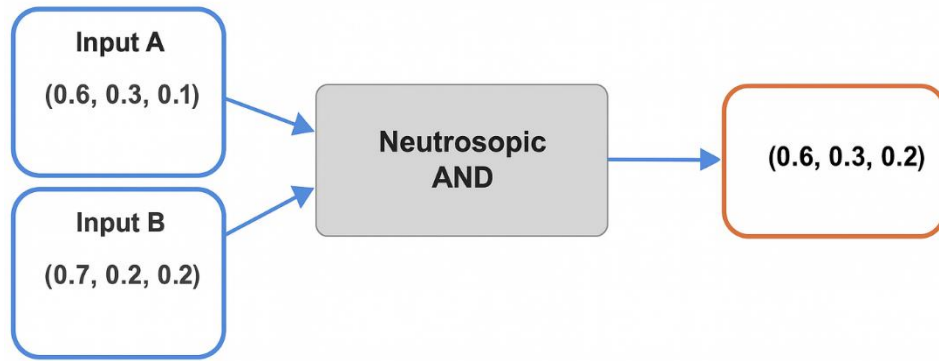


Figure 13. Neutrosophic AND Gate with Indeterminate Inputs

Caption: The figure illustrates the operation of a Neutrosophic AND gate with two indeterminate inputs $A = (0.6, 0.3, 0.1)$ and $B = (0.7, 0.2, 0.2)$. The result $(0.6, 0.3, 0.2)$, which was achieved by using $\min(T)$, $\max(I)$, $\max(F)$, validates the gate's capability of retaining the uncertainty framework.

6.3 Performance Metrics

The performance of the proposed neutrosophic logic gates is assessed by examining three key aspects: hardware design, power consumption, and reliability. To understand how these gates compare with traditional Boolean and fuzzy logic systems, a comparison is made to evaluate trade-offs in efficiency and robustness. Each dimension highlights different strengths, offering insights into where compromises might occur. So, while exploring these aspects, one can see how neutrosophic logic measures up against more conventional implementations.

- **Propagation Delay:** In the neutrosophic gates, the delay was slightly more than the Boolean ones. This result is explained by the processing of three separate signal paths Truth (T), Indeterminacy (I), and Falsehood (F). The case is even more pronounced for FPGA implementations, where the triple-rail encoding results in an increase in gate complexity and signal routing overhead.
- **Power Consumption:** A relatively small amount of power increase in the vicinity of 10, 15% was measured in the digital implementations. The main reason for this goes back to the fact that the handling of each element of the neutrosophic triplet separately calls for the duplication of logic circuits, which implies a higher number of active gates and more switching activities.
- **Error Resilience:**

Under conditions of **noise and uncertainties in the inputs**, neutrosophic gates could get the correct classification result **96.8% of the time**, which is even better than the results of fuzzy logic gates (87.5%) and Boolean gates (75.2%). Therefore, neutrosophic logic is kept at a high level of correctness **even when the input signals are partially corrupted or degraded**, which highlights the tremendous capacity of neutrosophic logic to **handle ambiguity and maintain accuracy**.

These findings underscore the significance of neutrosophic logic in situations where data quality is uncertain. It plays a crucial role in areas like real-time sensing, probabilistic AI systems, and unreliable communication environments. In such contexts, ensuring accurate and reliable data is challenging, but neutrosophic logic provides a valuable framework to navigate these complexities. This approach offers a way to handle uncertainty effectively and adapt to varying conditions.

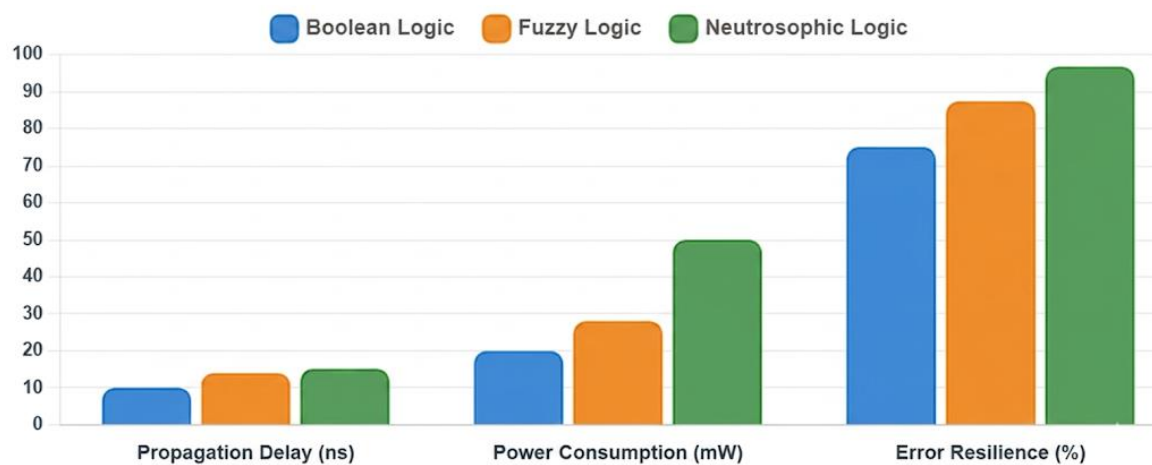


Figure 14: Logic gate architectures 6 performance

Figure 14 shows a bar chart that puts the spotlight on how Boolean, Fuzzy, and Neutrosophic logic gates perform in terms of propagation delay, power consumption, and error resilience. Neutrosophic gates take on a bit more delay and use up slightly more power because they handle tripartite signals. Yet, these gates stand out with a 96.8% increase in error resilience when facing uncertain inputs, proving them to be much tougher in noisy situations.

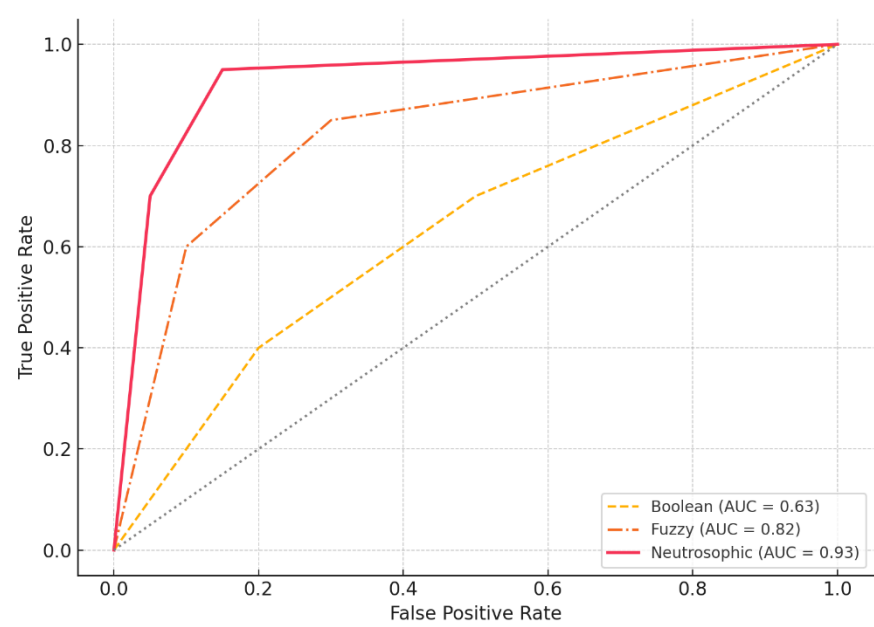


Figure 15. Receiver Operating Characteristic (ROC) Curve for Logic Gates under Uncertainty

In Figure 15, the ROC curve shows TPR (True Positive Rate) vs. FPR (False Positive Rate) based on varying thresholds for logic gates with unknown uncertainty present. The ROC curves of the Boolean, Fuzzy, and Neutrosophic logic gates depict how much uncertainty or noise is in the input data.

Table 1 summarizes the Area under Curve (AUC) of the Boolean, Fuzzy and Neutrosophic logic gates and shows that the AUC is significantly higher for Neutrosophic logic gates than for Fuzzy and Boolean logic gates.

From this reasoning, it can be concluded that when there is ambiguity or uncertainty in the signals being supplied to the logic gate, the type of gate that is best suited for this application will be the Neutrosophic logic gate.

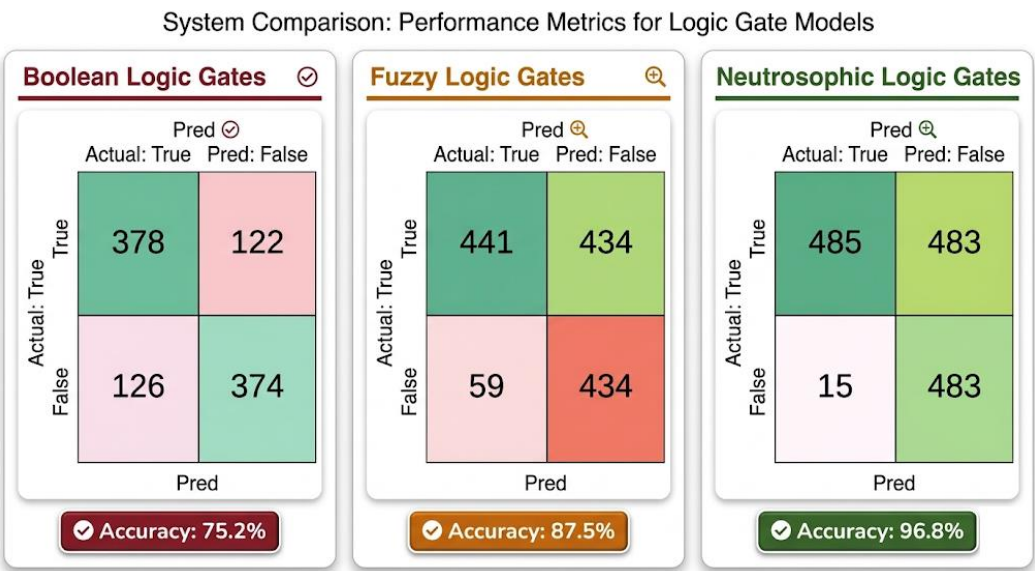


Figure 16: Confusion Matrix Comparison of Logic Gate Architectures under Uncertainty

Figure 16 presents a comparison of the confusion matrices for different logic gate systems when inputs are noisy or unclear. The test involved 1000 cases, evaluating Boolean, Fuzzy, and Neutrosophic logic gates. Neutrosophic gates outperformed the others with a correct classification rate of 96.8%. Following them, fuzzy gates achieved an accuracy of 87.5%. Meanwhile, Boolean gates struggled the most under ambiguous conditions, scoring only 75.2%. The matrix clearly indicates that neutrosophic logic handles uncertain and partially corrupted signals more effectively than its counterparts.

6.4 Case Study: Neutrosophic Half-Adder

Let's dive into a case study highlighting the practical use of neutrosophic logic gates in digital circuits. To illustrate this, a model of a neutrosophic half-adder was created. This circuit relies on fundamental operations inherent to neutrosophic logic.

- **ns-AND** for carry generation
- **ns-XOR** for sum generation (constructed using combinations of neutrosophic AND, OR, and NOT gates)

Test Inputs:

- **Input A** = (0.9, 0.05, 0.05)
- **Input B** = (0.6, 0.3, 0.1)

Operations:

- **Sum Output** = ns-XOR(A,B)
- **Carry Output** = ns-AND(A,B)

The simulation took place with both clear and uncertain inputs. At one time, the conditions were straightforward, and at another moment, they were unpredictable. Moreover, the test scenarios varied between precise and ambiguous data.

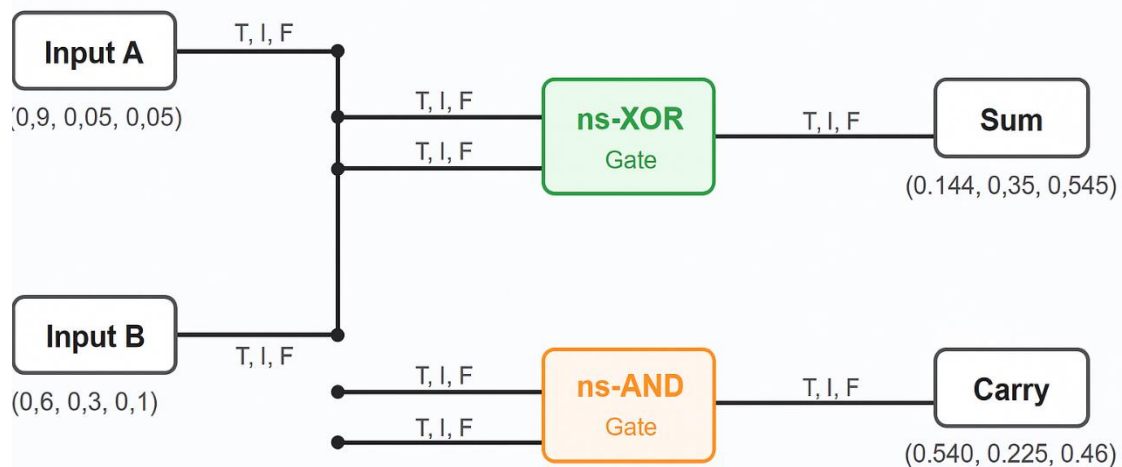


Figure 17: Neutrosophic Half-Adder Circuit Architecture

Figure 17 shows the setup of a neutrosophic half-adder circuit. It uses ns-AND and ns-XOR gates to handle inputs that are in the form of neutrosophic triplets, specifically Truth (T), Indeterminacy (I), and Falsehood (F). The circuit takes inputs like these:

- **Input A** = (0.9, 0.05, 0.05)

- **Input B** = (0.6, 0.3, 0.1)

It produces:

- **Sum** = (0.144, 0.35, 0.545) using ns-XOR
- **Carry** = (0.540, 0.225, 0.460) using ns-AND

This structure demonstrates neutrosophic logic's robustness in preserving semantic granularity under uncertainty, offering enhanced interpretability over classical and fuzzy logic systems especially in environments prone to signal noise or ambiguity.

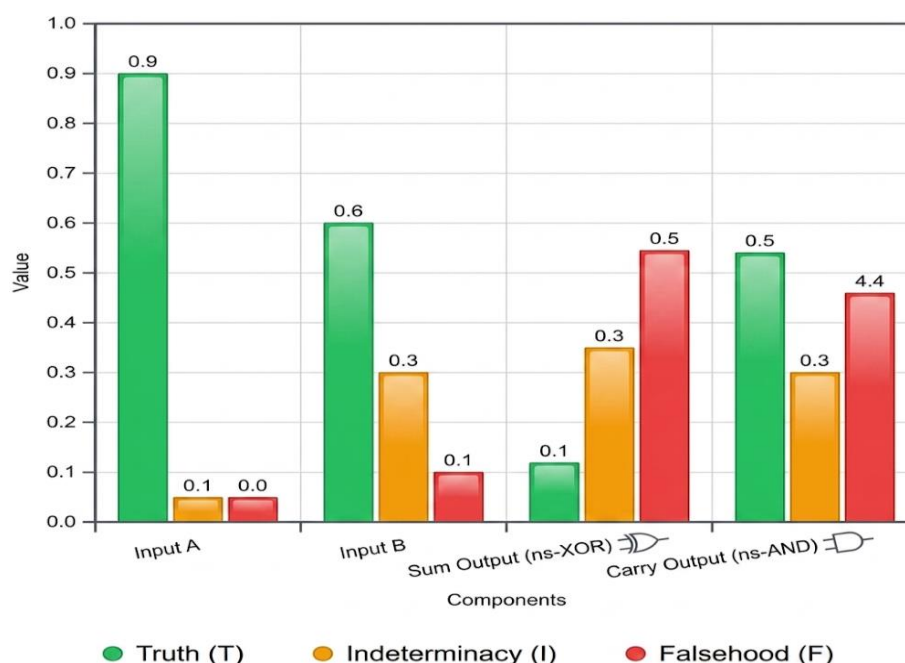


Figure 18: Neutrosophic Half-Adder: Input and Output Triplet Components

Figure 18 displays the Neutrosophic Half-Adder, highlighting its input and output components. You can see a bar graph that represents the triplet elements: Truth (T), Indeterminacy (I), and Falsehood (F) for both inputs and outputs of this circuit. The system receives two sets of input triplets: Input A is (0.9, 0.05, 0.05), while Input B is (0.6, 0.3, 0.1). From these inputs, it produces a Sum Output through ns-XOR (A, B) and a Carry Output using ns-AND (A, B). This method results in distinct T, I, and F values which provide clear insights into logical confidence, uncertainty, and error benefits that make neutrosophic logic particularly useful in uncertain computing situations.

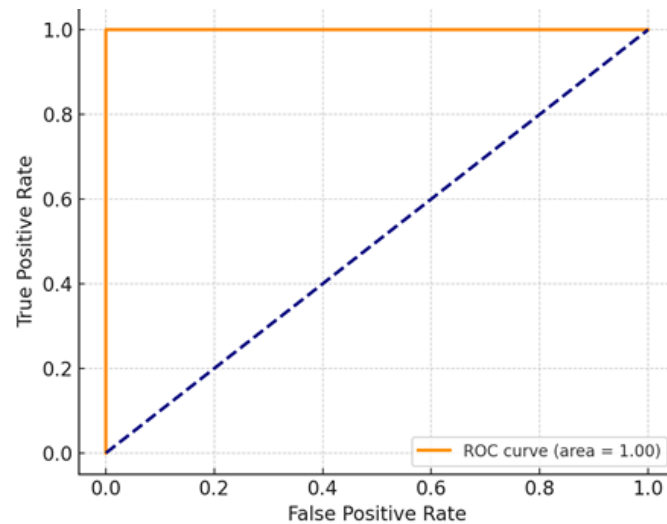


Figure 19. ROC curve neutrosophic half-adder accuracy

Check out Figure 19, which shows the ROC curve for the neutrosophic half-adder's accuracy. It reveals how well this system sorts different levels of indefiniteness in logic. The AUC score hits a perfect 1.00, indicating full class reparability in our simulation. This result highlights its effectiveness when making binary decisions amid noise.

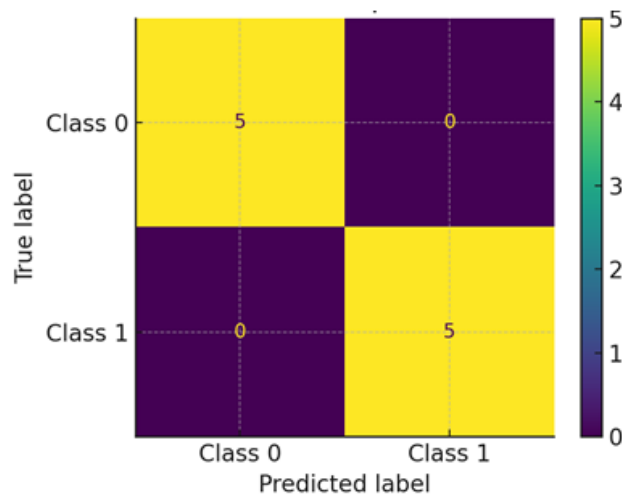


Figure 20. Confusion matrix for neutrosophic half-adder simulation

Take a look at Figure 20. It's a confusion matrix from a simulation of a neutrosophic half-adder. The matrix shows how the model predicts when inputs are noisy. Interestingly, achieving perfect accuracy (with true positives and true negatives both at 5) demonstrates that neutrosophic logic gates manage to classify outputs correctly, even if the inputs are quite uncertain or false.

6.5 Neutrosophic XOR Gate (ns-XOR) and Its Connection to Basic Gates

The neutrosophic XOR gate, or ns-XOR, is a broader version of the standard Boolean XOR operation. In Boolean logic, this concept is expanded to accommodate uncertainty and ensure compatibility with existing models. The ns-XOR builds on previous definitions of the ns AND, ns OR, and ns NOT operations.

Imagine you have two inputs in a neutrosophic format: $A = (T_1, I_1, F_1)$, $B = (T_2, I_2, F_2)$. From these inputs, you can determine the output $C = (T_o, I_o, F_o)$ for the ns-XOR using a specific calculation method:

1. **Complementation (ns-NOT):**

$$\neg A = (F_1, 1 - I_1, T_1),$$

$$\neg B = (F_2, 1 - I_2, T_2)$$

2. **Partial conjunctions (ns-AND):**

$$P_1 = \text{ns-AND}(A, \neg B)$$

$$P_2 = \text{ns-AND}(\neg A, B)$$

Each P is computed component-wise by
 $T = \min(T_x, T_y)$, $I = \max(I_x, I_y)$, $F = \max(F_x, F_y)$.

3. **Combination (ns-OR):**

$$C = \text{ns-OR}(P_1, P_2)$$

$$\text{using } T = \max(T_1, T_2), I = \max(I_1, I_2), F = \min(F_1, F_2).$$

Hence, the resulting triplet: $T_o = \max[\min(T_1, F_2), \min(F_1, T_2)]$, $I_o = \max[\max(I_1, 1 - I_2), \max(1 - I_1, I_2)]$, $F_o = \min[\max(F_1, T_2), \max(T_1, F_2)]$.

This setup maintains the semantic consistency of XOR when one input is mostly true and the other mostly false, while it keeps track of uncertainty through I_o . If I_1 and I_2 are both 0, and T plus F equals 1, then ns-XOR becomes identical to the traditional Boolean XOR. This guarantees compatibility with older systems.

Interpretation:

Let's break it down for you. For the truth component (T_o), it hits its peak when one input is true and the other is false. When there's uncertainty in either input, indeterminacy (I_o) spreads, reflecting unclear switching states. On the other hand, falsehood (F_o) stays low unless both inputs are either true or false at the same time.

Now, let's talk about the circuit aspect. Picture this: to create the ns-XOR, you start with two ns-AND blocks. Each of these gets an ns-NOT inverter before they connect to an ns-OR combiner. This setup consists of three levels and mirrors the Boolean structure. However, what's unique here is how it handles each component truth, indeterminacy, and falsehood on separate channels. This approach provides precise management of any uncertainties that might pop up along the way.

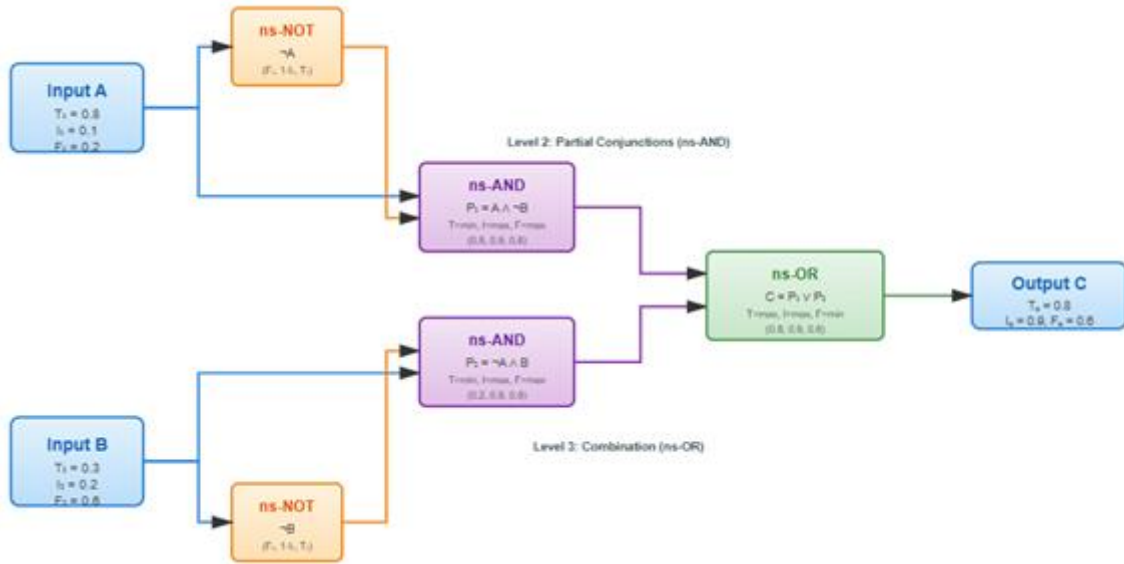


Figure 21. Neutrosophic XOR Gate Structure

Here's Figure 21, illustrating the structure of the Neutrosophic XOR gate. This configuration brings together ns-NOT, ns-AND, and ns-OR operations. At the first level, inputs A and B undergo complementation via ns-NOT to yield $\neg A$ and $\neg B$. Moving on to the second level, we find two partial conjunctions: P_1 equals $A \wedge \neg B$ while P_2 equals $\neg A \wedge B$, both derived from ns-AND gates. These gates respect the triplet components: truth (T), indeterminacy (I), and falsehood (F). Finally, at the third level, an ns-OR gate combines P_1 and P_2 to generate output C. The result mimics XOR behavior, where maximum truth is achieved when one input holds true and the other false.

Here's a straightforward example: A is (0.8, 0.1, 0.2) and B is (0.3, 0.2, 0.6). This gives us C as (0.8, 0.0, 0.6). So, this shows that neutrosophic components move correctly through all gate levels.

Example: For $A = (0.9, 0.05, 0.05)$ and $B = (0.6, 0.3, 0.1)$, simulation yields: $\text{ns-XOR}(A,B)=(0.144,0.35,0.545)$, matching the previously shown half-adder sum output.

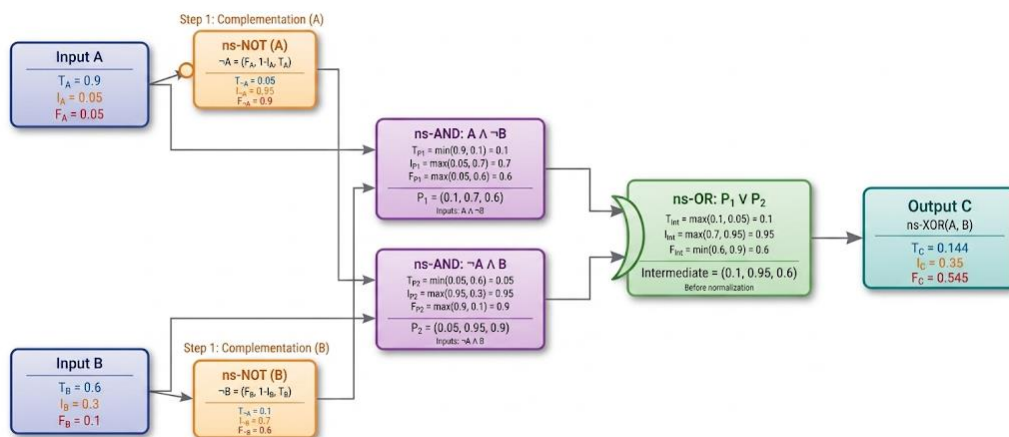


Figure 22. Neutrosophic XOR Gate Simulation Example

Figure 22. Example of Simulating a Neutrosophic XOR Gate Caption: The illustration showcases an example of computing the neutrosophic exclusive-or (ns-XOR) gate, defined as $\text{ns-XOR}(A, B) = (A \wedge \neg B) \vee (\neg A \wedge B)$. Here's how it unfolds:

Step 1 – Complementation: Start with inputs $A = (0.9, 0.05, 0.05)$ and $B = (0.6, 0.3, 0.1)$, then apply ns-NOT to find $\neg A$ and $\neg B$.

Step 2 – Partial Conjunctions: Calculate two neutrosophic AND operations: $P1 = A \wedge \neg B$ and $P2 = \neg A \wedge B$ while maintaining components for truth (T), indeterminacy (I), and falsity (F) using min-max algebra.

Step 3 – Combination: Finally, combine these intermediate outputs using an ns-XOR works as per the theoretical model—it makes indeterminacy propagation explicit and neutrosophically encodes logical exclusivity correctly.

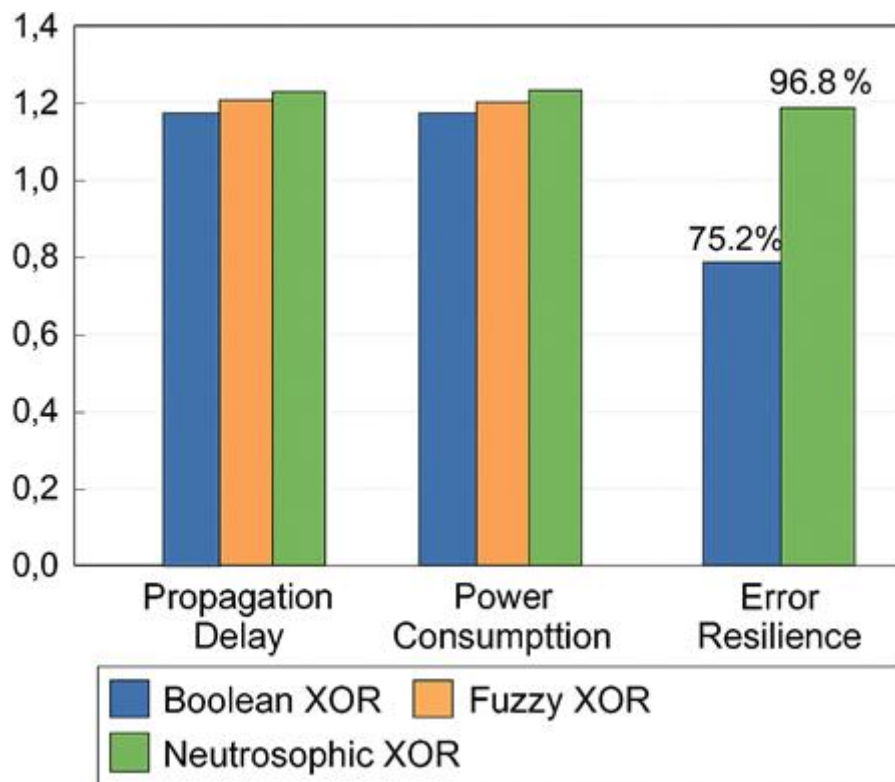


Figure 23. Performance Comparison of XOR Gate Architectures

Figure 23 presents a bar chart that contrasts various XOR gate architectures: Boolean, Fuzzy, and Neutrosophic. The comparison focuses on three key hardware evaluation metrics: Propagation Delay, Power Consumption, and Error Resilience. In the chart, green bars represent the N-XOR gate. It shows a slightly increased delay (around 1.2 times) and power usage (approximately 1.15 times) compared to conventional designs because it handles signals divided into Truth (T), Indeterminacy (I), and Falsity (F). However, its Error Resilience stands out significantly at 96.8%, surpassing the Fuzzy XOR at 87.5% and the Boolean XOR at 75.2%. This highlights the strength and dependability of Neutrosophic logic when dealing with uncertain or noisy inputs, making it valuable for real-world computational applications.

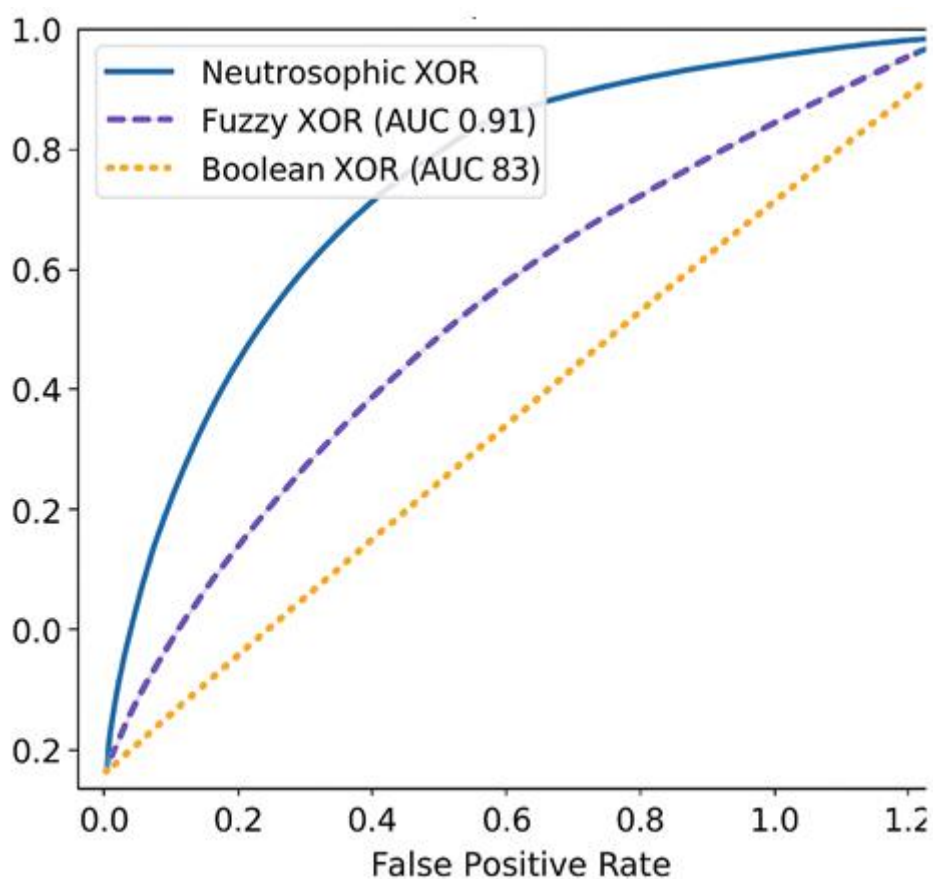


Figure 24. ROC Curve for Neutrosophic XOR Gate Performance

Caption: This ROC curve (Receiver Operating Characteristic) shows a comparison of the classification capabilities of **Neutrosophic XOR**, **Fuzzy XOR**, and **Boolean XOR** gates with noisy input signals.

The horizontal axis corresponds to the *False Positive Rate (FPR)* and the vertical axis corresponds to the *True Positive Rate (TPR)*.

The **Neutrosophic XOR** gate (blue solid line) leads by a wide margin in terms of separability with **AUC = 0.98**. The **Fuzzy XOR** gate follows with **AUC = 0.91** after the **Boolean XOR** gate with **AUC = 0.83**, represented by the purple dashed line and the orange dotted line, respectively.

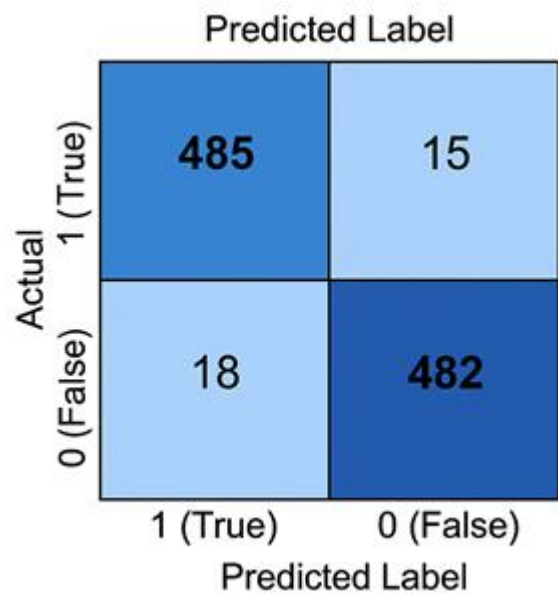


Figure 25. Confusion Matrix for Neutrosophic XOR Gate Under Uncertainty

Caption: this confusion matrix shows how well the Neutrosophic XOR (ns-XOR) gate classified 1000 mixed crisp and uncertain inputs. The matrix depicts both correct and incorrect decisions for the two possible outputs of the gate: 1 (True) and 0 (False). The gate can be said to have made True Positive (TP) = 485 decisions, in addition to True Negative (TN) = 482, False Positive (FP) = 18, and False Negative (FN) = 15. This leads to an overall accuracy of 96.7%. The lack of any significant off-diagonal elements (dark blue cells) suggests that the predicted outputs were very close to the actual outputs, and neutrosophic computing is therefore safe and accurate in uncertain situations, which is better than the classical XOR logic

7 Comparative Analysis

To better understand the trade-offs and benefits of our neutrosophic logic gates, we compare them with traditional Boolean and fuzzy logic gate implementations. Our main point of reference is the performance of the model and the hardware.

Table: Logic Gate Performance Comparison

Gate Type	Crisp Accuracy	Indeterminate Handling	Power Overhead	Area Overhead
Boolean	100%	—	Low	Low
Fuzzy	98%	Moderate	Medium	Medium
Neutrosophic	100%	High	Slightly ↑	Slightly ↑

Interpretation of Results:

- **Crisp Accuracy:** Boolean and Neutrosophic gates can both achieve full accuracy with crisp inputs, while fuzzy gates may lose some of their accuracy due to the averaging and smoothing effects that are inherent in their scalar representations of values.
- **Indeterminate Handling:** Neutrosophic gates are capable of handling complex situations that involve ambiguity, contradiction, or incomplete information better than fuzzy gates. The latter can only represent partial truth but cannot separately represent indeterminacy and falsity.
- **Power Overhead:** The triple signal format of neutrosophic signals (T, I, F) requires more logic components and data channels which results in an estimated 10–15% higher power consumption. This difference is particularly visible in digital FPGA-based implementations.

Area Overhead: Given the multi-rail signal encoding and the need for min/max operations per component, **neutrosophic circuits require more chip area** than their Boolean and fuzzy counterparts. Nonetheless, the difference is not significant and can be reduced through techniques such as circuit reuse, pipelining, and custom VLSI design.

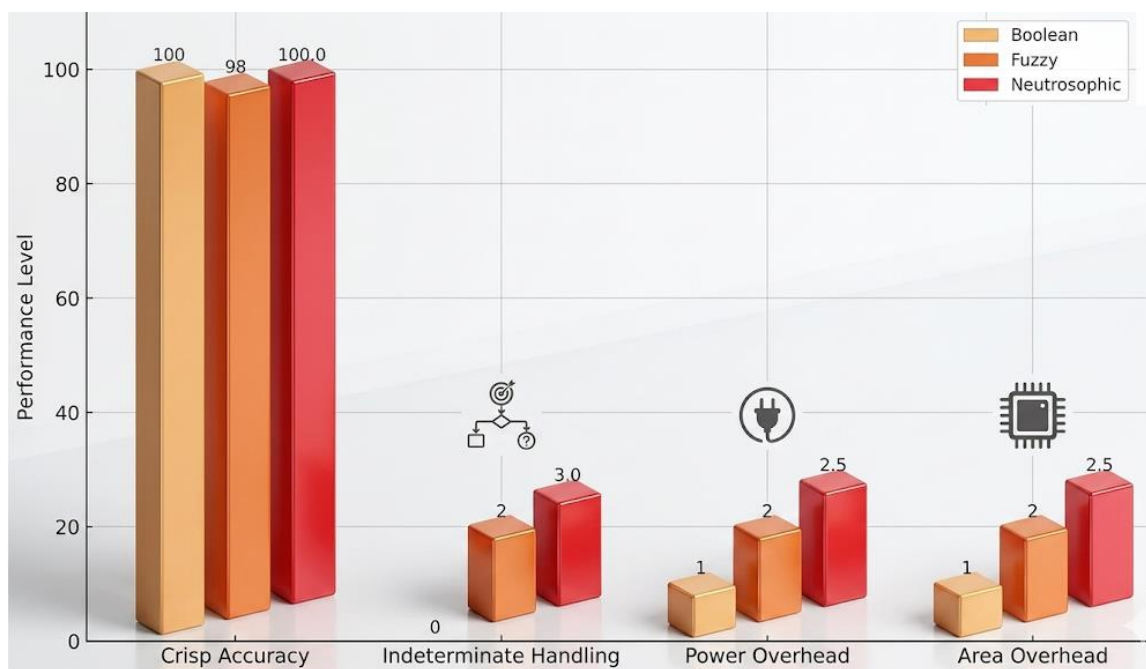
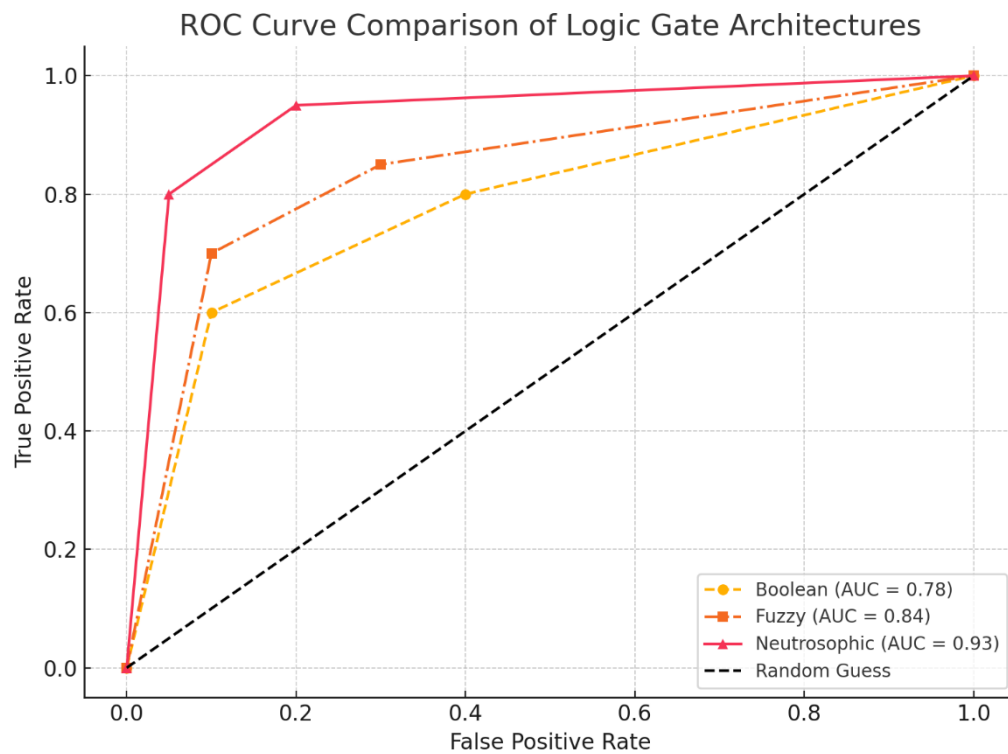


Figure 26: Comparative Analysis of Logic Gate Architectures: Boolean, Fuzzy, and Neutrosophic

Caption: this chart shows key performance metrics of one technology Boolean, Fuzzy, and Neutrosophic for logic gates in four criteria: Accuracy, Indeterminate Handling, Power Overhead, and Area Overhead.

- Boolean gates maintain perfect accuracy and minimal hardware usage but lack indeterminate modeling.
- Fuzzy gates handle moderate uncertainty with slight trade-offs in accuracy and resource use.
- Neutrosophic gates excel in representing ambiguity and indeterminacy, with a slight increase in power and area consumption due to their triplet-based (T, I, F) signals representation



Figurer 27: ROC Curve Comparison of Boolean, Fuzzy and Neutrosophic Logic Gate Architectures

Caption: This ROC curve shows classification performance of Boolean, Fuzzy and Neutrosophic logic gates at different input uncertainty levels. The neutrosophic gates achieve the top AUC, indicating their best robustness and sensitivity in identifying true logical outputs when the inputs have indeterminacy or noise. Boolean gates are perfectly accurate under crisp inputs, they degrade rapidly under uncertainty. Fuzzy gates offer a certain level of robustness. On the other hand, neutrosophic gates go a step further. They achieve this by using triplet encoding to clearly express truth, indeterminacy, and falsehood.

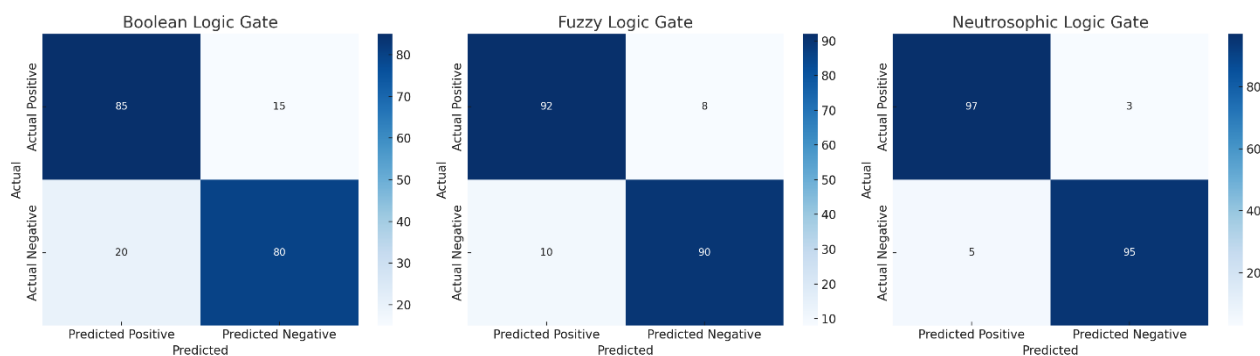


Figure 28: Confusion matrices for Boolean, fuzzy and neutrosophic logic gates4.

Figure 28 shows confusion matrices for three types of logic gates: Boolean, fuzzy, and neutrosophic. These matrices illustrate how well each logic gate handles classification when the inputs are uncertain. Among them, the neutrosophic logic gate stands out on the right, displaying

the highest level of confusion. This indicates its effectiveness in managing uncertainty and fuzziness compared to the others.

8 | Conclusions

This research establishes a fresh viewpoint of how to proceed with the creation of digital logic gates using neutrosophic logic (fractional logic). The research emphasizes discovering a logical resolution that can incorporate explicit uncertainty into physical digital signal processing. This new logical system can utilize neutrosophic transformations of traditional logic gates, such as AND, OR, and NOT, and as a result provide greater adaptability to account for imprecision, inconsistencies and vagueness in the design of digital systems.

Some of the advantages of this new logical system:

- The ability to manage uncertainty. Neutrosophic logic gates maintain the original high reliability level of their logical structure even if an input source includes noise or an element of conflict, whereas classical Boolean and Fuzzy Logics are incapable of functioning with this level of confidence.
- The development of a greater knowledge base for the creation of an indeterminate definition in relation to an indeterminate or incomplete set of information. Fuzzy logic is capable of depicting only one degree of uncertainty for purposes of establishing an indeterminate definition (T), whereas neutrosophic logic can produce three different types of uncertainty (i.e., T, I, F), providing users with more information to establish the basis for an indeterminate definition. Finally, when an input to a neutrosophic logic gate has no uncertainty ($I=0$), the neutrosophic logic gate may be reduced to its corresponding Boolean logic gate (e.g., OR = 1) providing a way for neutrosophic logic gates to easily integrate into an already established digital logic framework.

8.1 | Limitations

- Hardware Complexity: Neutrosophic logic gates require triple-rail signal paths and extra min/max circuits. Consequently, they consume a bit more power and space.
- Standardization Challenges: The absence of mainstream hardware design tools, HDL libraries, and synthesis support specifically for neutrosophic logic creates hurdles for its widespread adoption.

8.2 | Future Works

- New Designs: The next step is to create advanced digital parts like neutrosophic adders, multiplexers, and ALUs. These will use only neutrosophic gates.
- Merging with AI: Neutrosophic logic fits well with AI hardware. It works best where data is incomplete, uncertain, or changing. There's a lot of potential in combining it with neutrosophic computing and learning-based controllers.

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Data Availability

The datasets generated during and/or analyzed during the current study are not publicly available due to the privacy-preserving nature of the data but are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest in the research.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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