# A Comprehensive Review on Tool Geometry Optimization in Drilling Processes for Enhancing Machining Performance

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*Abstract*—**Drilling is one of the most important machining operations used in manufacturing industries, where drilling performance is significantly influenced by drill tool geometry and machining conditions. This review paper presents a comprehensive overview of the influence of tool geometry parameters, including point angle, helix angle, rake angle, clearance angle, and chisel edge geometry, on drilling quality, cutting forces, burr formation, tool wear, and hole accuracy. Recent developments in experimental investigations, statistical modelling, finite element analysis, and multi-objective optimization techniques are critically reviewed to evaluate their effectiveness in improving machining performance. The paper also discusses the application of modern optimization approaches such as Response Surface Methodology, Grey Relational Analysis, Genetic Algorithms, Particle Swarm Optimization, and artificial intelligence-based methods for drill design optimization. Furthermore, current research trends, existing challenges, research gaps, and future opportunities related to sustainable manufacturing and Industry 4.0-enabled intelligent drilling systems are highlighted. The review concludes that integrated optimization of drill geometry and machining parameters can significantly improve productivity, machining quality, tool life, and overall manufacturing efficiency while supporting sustainable and smart manufacturing practices.**

*Index Terms*—**Drilling Process, Tool Geometry Optimization, Machining Performance, Statistical Modelling, Multi-Objective Optimization**

## I. Introduction

### 1.1 Background of Drilling Processes

Drilling is one of the most widely employed machining operations in modern manufacturing for producing circular holes in engineering materials. It is extensively used in automotive, aerospace, railway, medical, and heavy engineering industries because most mechanical components require accurately drilled holes for assembly and fastening. The performance of the drilling process depends on machining conditions, drill geometry, workpiece material, and machine tool rigidity. Continuous advancements in cutting tool technology and process optimization have significantly improved drilling efficiency and product quality [1], [6], [15].

### 1.2 Importance of Tool Geometry in Drilling Performance

Tool geometry directly affects chip formation, cutting forces, heat generation, tool wear, and dimensional accuracy. Proper selection of drill point angle, helix angle, clearance angle, and web thickness improves chip evacuation, reduces thrust force, and enhances hole quality. Therefore, drill geometry optimization is considered an essential aspect of machining research [1], [2], [10].

### 1.3 Challenges in Conventional Drill Design

Conventional twist drills frequently experience problems such as excessive burr formation, rapid tool wear, poor surface finish, inaccurate hole dimensions, and high cutting temperatures. These challenges reduce machining efficiency and increase production cost, particularly while machining difficult-to-cut materials [3], [11].

### 1.4 Need for Tool Geometry Optimization

Optimization of drill geometry improves machining quality, enhances productivity, reduces energy consumption, and extends tool life. Advanced optimization techniques combined with statistical modelling provide systematic approaches for selecting suitable drill geometry and machining conditions [7], [9], [24].

### 1.5 Objectives and Scope of the Review

This review aims to summarize recent developments in drilling tool geometry optimization, discuss the influence of geometric parameters on drilling performance, compare optimization techniques, and identify future research opportunities. The review covers drilling fundamentals, optimization methodologies, statistical modelling, simulation techniques, and intelligent manufacturing approaches.

### 1.6 Organization of the Review Paper

The review paper consists of three chapters. Chapter 1 presents the introduction and research motivation. Chapter 2 discusses drilling fundamentals, tool geometry, workpiece materials, and performance indicators. Chapter 3 reviews optimization methods, statistical analysis, numerical simulation, and artificial intelligence techniques used for drilling optimization.

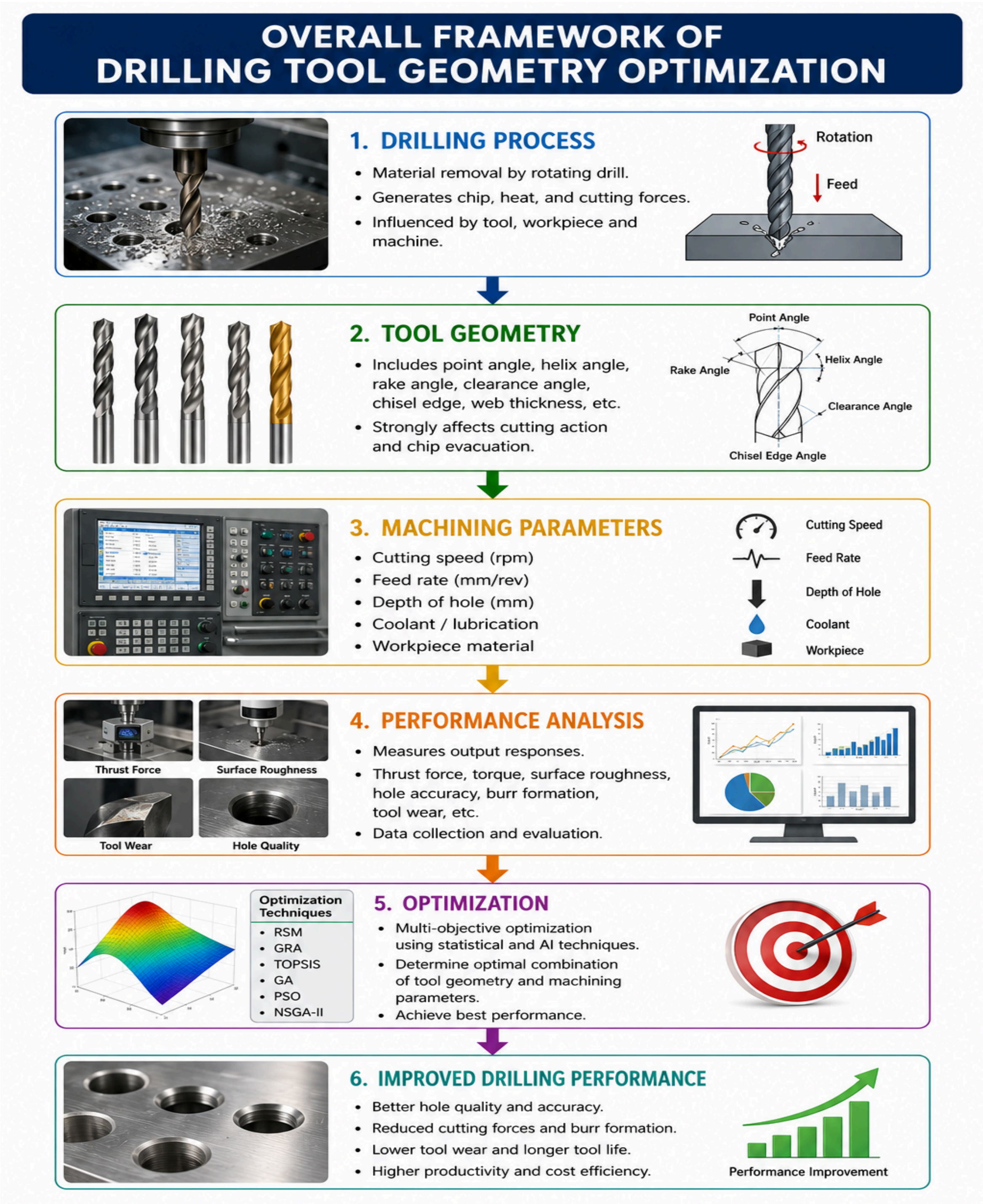


Figure 1.1 Overall Framework of Drilling Tool Geometry Optimization

**Table 1.1 Tool Geometry and Performance**

| Tool Geometry Parameter | Major Influence |
|---|---|
| Point Angle | Thrust force, burr formation |
| Helix Angle | Chip evacuation |
| Clearance Angle | Friction reduction |
| Web Thickness | Tool rigidity |
| Chisel Edge | Penetration force |

## II. Fundamentals of Drilling Process and Tool Geometry

### 2.1 Fundamentals of Drilling Operations

Drilling is a machining operation in which a rotating multi-point cutting tool removes material from a workpiece to produce cylindrical holes. The cutting action depends on rotational speed, feed motion, tool geometry, and workpiece characteristics. Proper machining conditions improve drilling efficiency and hole quality [5], [6].

### 2.2 Types of Drilling Processes

- **Conventional Drilling:** General-purpose drilling using standard twist drills.
- **High-Speed Drilling:** Higher spindle speed improves productivity and surface finish.
- **Deep Hole Drilling:** Used for holes having large depth-to-diameter ratios.
- **Micro Drilling:** Suitable for miniature precision components.
- **Dry and MQL Drilling:** Environmentally friendly machining with reduced coolant consumption [26], [29], [30].

### 2.3 Twist Drill Construction

A twist drill consists of the shank, body, flutes, cutting lips, web, chisel edge, margins, and drill point. These elements collectively determine drilling efficiency, chip removal, rigidity, and cutting performance [16]–[22].

### 2.4 Tool Geometry Parameters

Important drill geometry parameters include:

- Point Angle
- Helix Angle
- Rake Angle
- Clearance (Relief) Angle
- Chisel Edge Angle
- Web Thickness
- Margin Width
- Lip Length
- Flute Geometry

These parameters significantly influence thrust force, torque, chip evacuation, heat generation, and tool life [1], [18], [20].

### 2.5 Workpiece Materials Used in Drilling

Drilling operations are performed on carbon steels, stainless steels, aluminium alloys, titanium alloys, cast iron, nickel-based superalloys, composites, and fibre-reinforced polymers. Material properties determine the selection of suitable drill geometry and machining conditions [4], [5], [23].

### 2.6 Drilling Performance Indicators

Major performance indicators include:

- Thrust Force
- Torque
- Surface Roughness
- Hole Accuracy
- Circularity
- Cylindricity
- Burr Formation
- Tool Wear
- Tool Life
- Material Removal Rate (MRR)

These responses are commonly used to evaluate drilling quality and optimize machining performance [2], [12], [28].


Figure 2.1 Construction of a Twist Drill

**Table 2.1 Drilling Performance Indicators**

| Performance Indicator | Significance |
|---|---|
| Thrust Force | Cutting load |
| Torque | Power requirement |
| Surface Roughness | Surface quality |
| Burr Formation | Hole finish |

| | |
|---|---|
| Tool Wear | Tool durability |
| Tool Life | Machining economy |
| MRR | Productivity |

## III. Tool Geometry Optimization Techniques and Performance Analysis

### 3.1 Influence of Tool Geometry on Machining Performance

Tool geometry significantly affects drilling performance by influencing chip formation, heat generation, cutting forces, burr formation, and tool wear. Optimized geometry improves hole quality and machining stability while extending tool life [7], [10], [21].

### 3.2 Experimental Design Approaches

Experimental optimization commonly employs:

- Design of Experiments (DOE)
- Full Factorial Design
- Taguchi Method

These approaches reduce the number of experiments while identifying the significant machining variables affecting drilling responses [24].

### 3.3 Statistical Modelling Techniques

Statistical techniques widely applied in drilling optimization include:

- Regression Analysis
- Analysis of Variance (ANOVA)
- Response Surface Methodology (RSM)

These methods establish mathematical relationships between machining variables and performance responses while identifying statistically significant factors [24].

### 3.4 Multi-Objective Optimization Techniques

Modern optimization techniques simultaneously optimize multiple machining responses.

Common methods include:

- Grey Relational Analysis (GRA)
- Desirability Function Analysis
- TOPSIS
- Genetic Algorithm (GA)
- Particle Swarm Optimization (PSO)
- NSGA-II

These techniques provide balanced optimization considering productivity, tool life, and machining quality [9], [24].

### 3.5 Finite Element Analysis (FEA) and Numerical Simulation

Finite Element Analysis enables prediction of stress distribution, temperature generation, chip formation, and tool deformation during drilling. Numerical simulation reduces experimental effort and assists in optimizing drill geometry before physical testing [7], [11].

### 3.6 Artificial Intelligence and Machine Learning in Tool Geometry Optimization

Artificial Intelligence techniques such as Artificial Neural Networks, Machine Learning, Genetic Algorithms, and hybrid optimization methods are increasingly used for predicting drilling responses and identifying optimum machining conditions. These intelligent approaches support data-driven process optimization and Industry 4.0 manufacturing systems [10], [15].

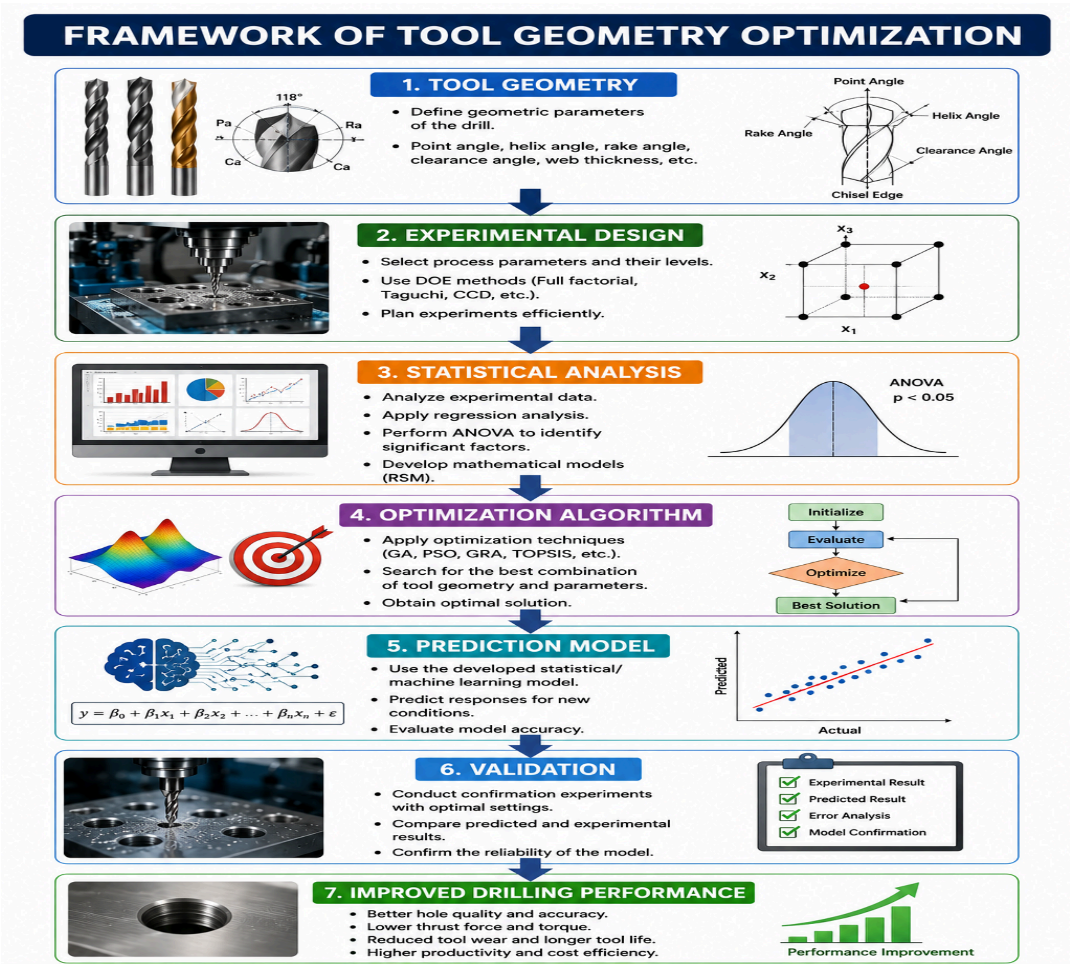


Figure 3.1 Framework of Tool Geometry Optimization

**Table 3.1 Optimization Techniques in Drilling**

| Technique | Application |
|---|---|
| DOE | Experimental planning |
| Taguchi | Robust parameter design |
| ANOVA | Significance analysis |
| Regression | Prediction modelling |
| RSM | Process optimization |
| GRA | Multi-response optimization |
| TOPSIS | Decision making |
| GA | Evolutionary optimization |
| PSO | Global optimization |

| | |
|---|---|
| NSGA-II | Multi-objective optimization |

## IV. Literature Review and Comparative Analysis

### 4.1 Review of Earlier Research on Tool Geometry

Previous research has demonstrated that drill geometry significantly affects machining performance, including thrust force, torque, burr formation, surface finish, and tool life. Early investigations mainly focused on drill point geometry, while recent studies have integrated experimental investigations with numerical simulation and optimization techniques. Modern research also considers coated drills, textured drills, and multi-margin drills to improve drilling efficiency and hole quality [1], [7], [8], [27], [28].

### 4.2 Comparative Analysis of Different Drill Geometries

Different drill geometries are designed to suit specific machining requirements. Conventional twist drills are suitable for general-purpose applications, whereas split-point, four-facet, multi-margin, and surface-textured drills improve chip evacuation, reduce thrust force, and enhance dimensional accuracy. Proper selection of drill geometry depends on workpiece material, machining conditions, and required hole quality [16]–[22], [27].

### 4.3 Comparative Study of Optimization Techniques

Researchers have applied various optimization methods including Design of Experiments (DOE), Taguchi Method, Response Surface Methodology (RSM), Grey Relational Analysis (GRA), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO). Statistical techniques effectively reduce experimental effort while accurately predicting machining responses. Hybrid optimization methods have shown improved capability for solving multi-response machining problems [9], [10], [24].

### 4.4 Influence of Tool Geometry on Various Workpiece Materials

The effect of tool geometry varies with workpiece material.

- **Steel:** Improved drill geometry reduces cutting force and improves surface finish.
- **Stainless Steel:** Proper geometry minimizes work hardening and improves tool life.
- **Aluminium Alloys:** Larger helix angles improve chip evacuation.
- **Titanium Alloys:** Optimized geometry reduces heat generation and burr formation.
- **Cast Iron:** Stronger drill geometry enhances dimensional accuracy.
- **Composite Materials:** Special drill geometries reduce delamination and improve hole quality [4], [5], [23], [27], [28].

### 4.5 Research Trends (2015–2026)

Recent research trends focus on simulation-based drill design, finite element analysis, AI-assisted optimization, sustainable drilling, dry and MQL machining, textured cutting tools, digital manufacturing, and Industry 4.0-enabled intelligent machining systems. Machine learning and multi-objective optimization are increasingly used for predictive modelling and process optimization [7], [11], [15], [30].

### 4.6 Summary of Literature Findings

The literature indicates that tool geometry optimization significantly improves drilling performance. Although numerous optimization methods have been proposed, integrated studies combining drill geometry, statistical modelling, finite element simulation, and artificial intelligence remain limited. Future research should emphasize intelligent, sustainable, and data-driven drilling systems.

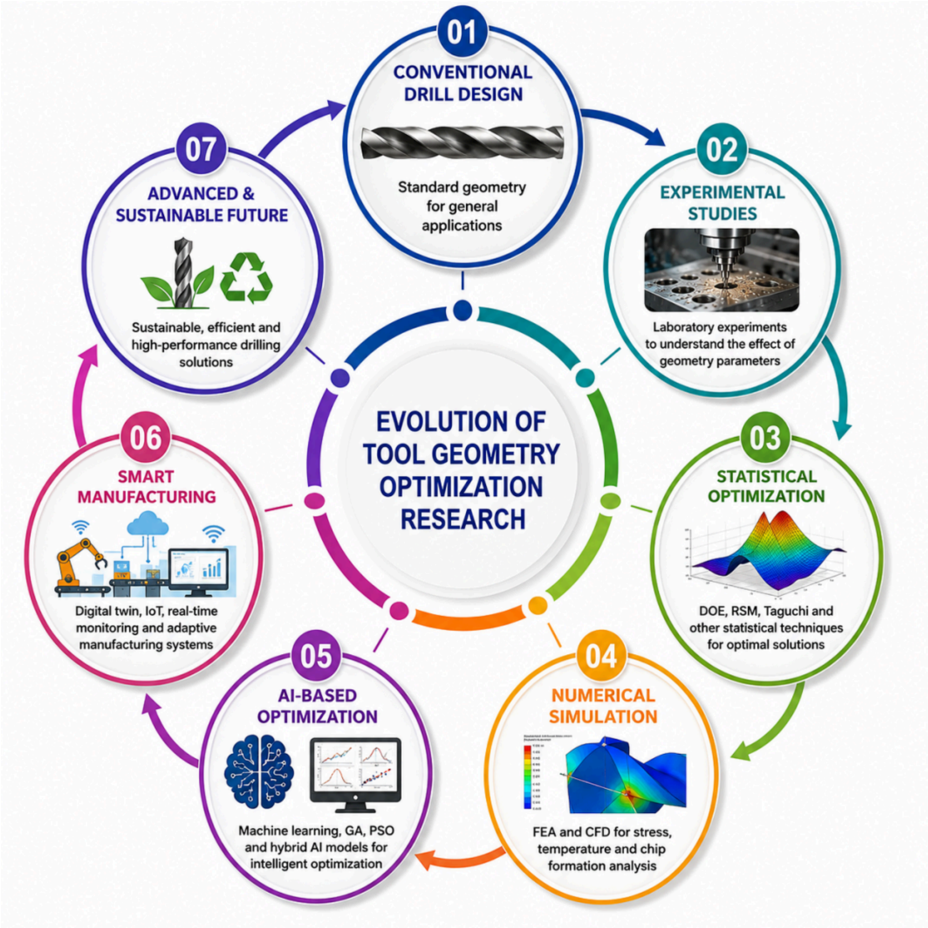


Figure 4.1 Evolution of Tool Geometry Optimization Research

**Table 4.1 Comparative Analysis of Drill Geometries**

| Drill Geometry | Major Advantage | Typical Application |
|---|---|---|
| Twist Drill | General-purpose drilling | Steel, Cast Iron |
| Split-Point Drill | Reduced thrust force | Stainless Steel |
| Four-Facet Drill | Better hole accuracy | Precision Machining |
| Multi-Margin Drill | Improved dimensional stability | Aerospace Components |
| Surface-Textured Drill | Reduced friction and burr formation | Titanium Alloys |

## V. Research Gaps, Challenges and Future Research Directions

### 5.1 Research Gaps Identified from Literature

Most published studies have focused on optimizing either machining parameters or individual drill geometry features. Limited research has investigated the combined influence of multiple tool geometry parameters using integrated experimental, statistical, and intelligent optimization techniques. Comprehensive predictive models suitable for industrial implementation remain limited [9], [10], [24].

### 5.2 Technical Challenges in Tool Geometry Optimization

Major technical challenges include complex chip formation, thermal effects, tool wear prediction, optimization of multiple responses, accurate modelling of drilling mechanics, and validation under different machining environments. Variations in workpiece materials further increase optimization complexity [11], [23], [29].

### 5.3 Industrial Challenges

Industries require drilling processes that simultaneously provide high productivity, excellent hole quality, low machining cost, and long tool life. Practical implementation of optimized drill geometries is often limited by production constraints, machine capability, and process variability.

### 5.4 Sustainable and Green Drilling Approaches

Current research promotes environmentally friendly machining through dry drilling, minimum quantity lubrication (MQL), reduced energy consumption, and improved cutting tool efficiency. Sustainable drilling aims to minimize waste generation and improve resource utilization [6], [9], [14].

### 5.5 AI-Driven Intelligent Tool Design

Artificial intelligence techniques including machine learning, neural networks, and evolutionary optimization algorithms provide effective tools for predicting machining responses and optimizing drill geometry. These approaches support intelligent manufacturing and adaptive process control [10], [15].

### 5.6 Digital Twin and Industry 4.0 Applications

Digital Twin technology, real-time monitoring, smart sensors, cloud computing, and predictive analytics enable continuous optimization of drilling operations. These technologies support data-driven manufacturing and improve process reliability through intelligent decision-making.

### 5.7 Future Research Opportunities

Future investigations should focus on hybrid optimization algorithms, AI-assisted drill design, digital twin-based drilling systems, sustainable machining, advanced coatings, additive manufacturing of cutting tools, and real-time process monitoring. Integration of simulation with experimental validation is expected to improve industrial applicability.

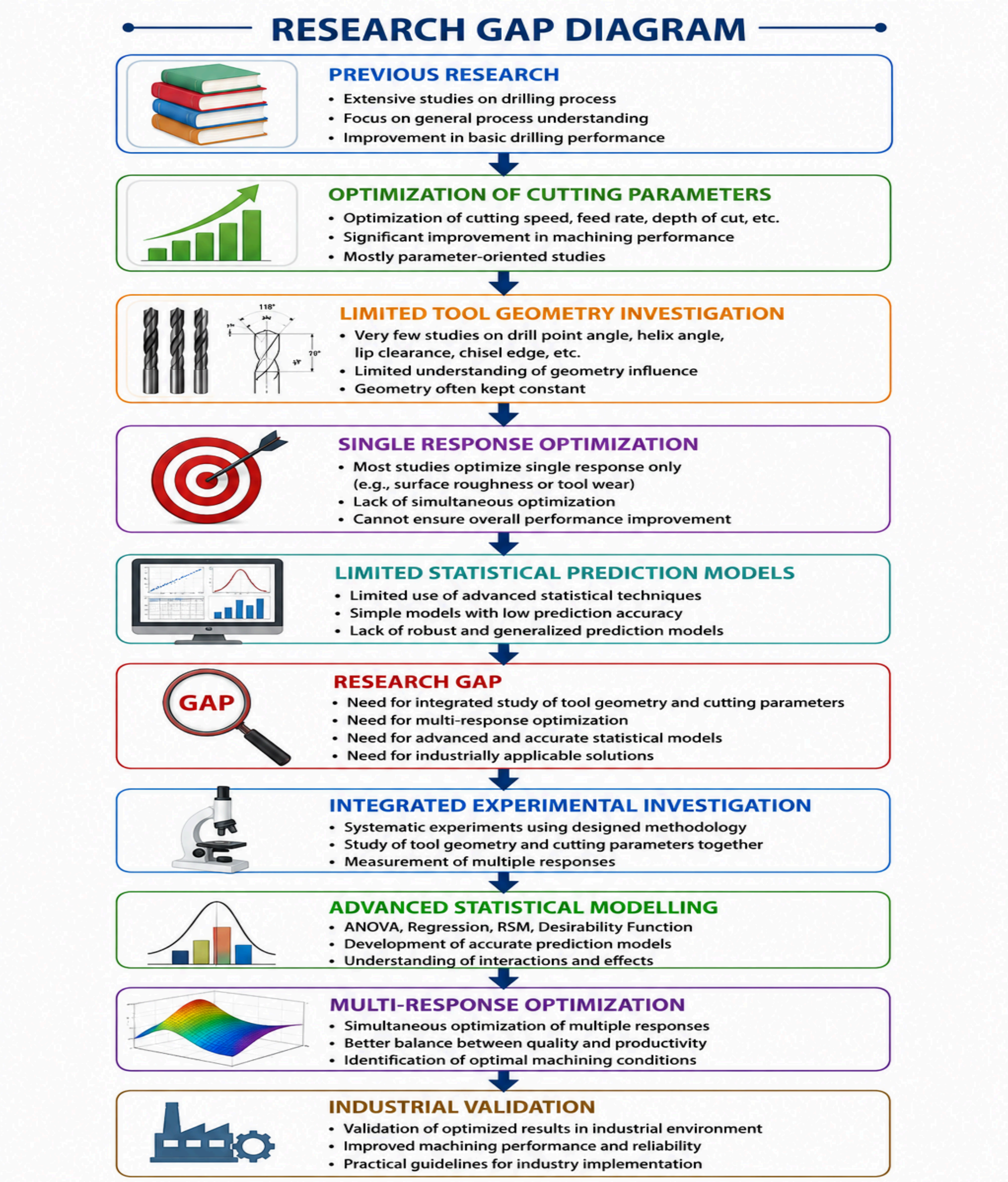


Figure 5.1 Future Research Framework

**Table 5.1 Research Gaps and Future Scope**

| Research Gap | Future Direction |
|---|---|
| Limited geometry optimization | Integrated optimization |
| Single-response studies | Multi-response optimization |
| Conventional modelling | AI and Machine Learning |
| Limited validation | Industrial implementation |
| High energy consumption | Sustainable drilling |

## VI. Conclusions

### 6.1 Summary of the Review

This review summarizes recent developments in drilling tool geometry optimization and highlights the influence of drill geometry on machining performance. It discusses drilling fundamentals, optimization techniques, statistical modelling, simulation approaches, and emerging intelligent manufacturing technologies. The review demonstrates that optimized drill geometry plays a significant role in improving drilling quality and productivity [7], [10], [24].

### 6.2 Major Findings

- Tool geometry significantly influences drilling performance.
- Statistical optimization methods improve prediction accuracy.
- Multi-response optimization provides balanced machining performance.
- Numerical simulation reduces experimental effort.
- AI-based optimization represents an emerging research direction.
- Sustainable drilling is becoming increasingly important for modern manufacturing.

### 6.3 Recommendations for Researchers

Future research should investigate integrated optimization of drill geometry and machining parameters using advanced statistical modelling, artificial intelligence, digital twin technology, and experimental validation. Hybrid optimization techniques and real-time monitoring should also receive greater attention.

### 6.4 Recommendations for Industrial Applications

Manufacturing industries should adopt optimized drill geometries, statistical process optimization, predictive modelling, and intelligent monitoring systems to improve machining quality, reduce production costs, and increase productivity. Sustainable drilling strategies should also be incorporated into modern manufacturing systems.

### 6.5 Concluding Remarks

Optimization of drill geometry remains an active and important research area in manufacturing engineering. The integration of experimental investigations, statistical analysis, finite element simulation, and artificial intelligence provides significant opportunities for improving drilling performance. Future developments in Industry 4.0 technologies are expected to further enhance intelligent and sustainable drilling processes.

**Table 6.1 Key Conclusions**

| Aspect | Conclusion |
|---|---|
| Tool Geometry | Major factor affecting drilling performance |
| Statistical Analysis | Enables reliable prediction and optimization |
| Simulation | Reduces experimental cost and time |
| Artificial Intelligence | Improves predictive capability |
| Sustainable Manufacturing | Supports energy-efficient machining |
| Industry 4.0 | Enables intelligent drilling systems |

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