Cyclomatic Complexity and Maintainability in Modern Software: A Systematic Review

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Abstract. Cyclomatic Complexity (CC) has emerged as a pivotal metric in contemporary software development, exhibiting robust correlations with testing initiatives and maintenance challenges. This systematic literature review analyzes five high-quality studies (2020-2024) covering more than 200 projects to evaluate the predictive value of CC in structural testing and maintenance contexts. The findings indicated substantial correlations between CC values and several key metrics, including: test coverage requirements (r=0.82), an augmented development time of 35-45% for CC>8, and a diminished code comprehension (r=-0.74). Research has demonstrated that CC values above 10-15 consistently predict test complexity and maintenance difficulty. Concurrently, the utilization of CC in CI/CD pipelines has reached 85% effectiveness as a quality gate, signifying its growing integration into software development processes. Nevertheless, challenges persist in the standardization of measurement and the necessity for a domain-specific threshold framework. The present study proposes the implementation of adaptive threshold-based CC, in conjunction with machine learning, to enhance the predictive quality analysis.

Keyword— Cyclomatic Complexity, Whitebox Testing, Software Quality Prediction, Structural Testing, Maintainability Correlation, Quality Metrics, CI/CD Integration

1. Introduction

In the contemporary software engineering landscape, delivering reliable, testable, and maintainable software systems remains a fundamental objective. As software complexity increases due to evolving requirements and expanding codebases, the ability to quantify and manage this complexity becomes essential. One of the most enduring and widely used metrics for this purpose is Cyclomatic Complexity, proposed by McCabe, which measures the number of linearly independent paths through a program's source code [1] .

Cyclomatic Complexity (CC) plays a critical role in structural testing, particularly in the white-box testing paradigm, where it serves as a guide for designing test cases that exercise all logical paths within a module. Unlike statement or branch coverage, CC-based path testing often referred to as basis path testing ensures that each decision point is evaluated independently, leading to a higher likelihood of fault detection and better coverage of potential execution flows [1].

Beyond testing, CC has also been widely integrated into software maintainability assessment models. A prominent example is the Maintainability Index (MI), which combines multiple software metrics including Cyclomatic Complexity, lines of code, and Halstead metrics to yield a single indicator representing how easily software can be maintained [2]. This is especially relevant

considering that maintenance activities often consume over 70% of total software project resources, with complexity being a key driver of maintenance cost and effort [3].
Research has shown that modules with high cyclomatic complexity tend to be more error-prone, harder to understand, and more difficult to modify [1], [4]. Accordingly, industry guidelines often suggest maintaining CC values below a certain threshold (typically 10) to ensure better software quality, reliability, and manageability. These guidelines are particularly important in large-scale or critical systems, where changes in complex modules may introduce regressions or latent defects if not properly tested [1].

Furthermore, in the context of object-oriented systems, the role of Cyclomatic Complexity remains significant. Although initially designed for procedural paradigms, studies have demonstrated its applicability in object-oriented environments, especially when combined with other maintainability metrics [3]. As such, CC continues to serve as both a predictive indicator of software quality and a foundation for structured testing methodologies in modern software development practices.

This paper investigates the utilization of Cyclomatic Complexity for enhancing structural testing effectiveness and evaluating software maintainability. By reviewing key methodologies, theoretical foundations, and empirical studies, we highlight how this metric can support informed decision-making in testing and maintenance processes, thereby contributing to more robust and sustainable software systems.

2. Literature Review

2.1. Cyclomatic Complexity and Structural Testing

Cyclomatic Complexity (CC), introduced by McCabe in 1976, is one of the most established metrics for quantifying the structural complexity of software modules [1]. It measures the number of linearly independent paths through a program's control flow graph, providing a direct indication of the decision-making complexity within a code module. As such, CC forms the basis of structured testing also referred to as basis path testing a white-box testing strategy that requires each independent path to be tested to ensure comprehensive logical coverage [1].

Watson and McCabe expanded this methodology through their structured testing model published under the National Institute of Standards and Technology (NIST), demonstrating that CC-based testing can uncover more defects than traditional approaches such as statement and branch coverage [1]. They also recommended that the CC of individual modules should not exceed 10 to preserve maintainability and testability.

2.2. Cyclomatic Complexity and Software Maintainability

There is a well-established relationship between software complexity and maintainability. Gill and Kemerer introduced the concept of Cyclomatic Complexity Density (CCD) defined as the average CC per function within a system as a more refined measure of maintainability productivity [2]. Their empirical study indicated that systems with high CCD values often exhibit lower maintenance productivity, underscoring the need to manage complexity as a means to facilitate more efficient software evolution.

To further quantify maintainability, researchers developed composite indicators such as the Maintainability Index (MI), which incorporates CC along with metrics like lines of code and Halstead's effort or volume to produce a single-valued estimate of maintainability [3]. This index provides a practical means for assessing the ease with which software can be understood and modified.

2.3. Maintainability Index in Object-Oriented Systems

While the MI was initially proposed for procedural software, recent research confirms its applicability in object-oriented systems. Heričko and Šumak conducted a comprehensive evaluation of various MI variants using 45 open-source Java-based systems and found that although the absolute values of MI differed between variants (e.g., with or without comment line ratios), their trends across versions were positively correlated [3]. This suggests that MI can reliably track maintainability evolution over time, even in object-oriented contexts.

Moreover, the Maintainability Index has been used beyond static evaluation. It has been applied in predictive modeling for technical debt detection and change-proneness analysis in modern systems. These applications reinforce the value of Cyclomatic Complexity not only as a metric for structured testing but also as a foundational component in maintainability evaluation and quality assurance processes.

3. Research Method

3.1. Research Approach

The present research employs a descriptive exploratory literature review approach. This approach aims to explore and map in depth the utilization of Cyclomatic Complexity as one of the metrics in the software structural testing process, and to examine how this metric plays a role in supporting software maintainability [2]. The decision to undertake a literature study was predicated on its capacity to furnish a comprehensive conceptual foundation and an empirical review, drawing upon extant and scientifically validated research.

$$CC(G) = E - N + 2P \quad (1)$$

3.2. Data Sources

The present study is supported by secondary data obtained from a variety of academic publications and other scientific sources that have undergone the peer review process. The data was collected from digital platforms that provide indexed international and national journals, such as IEEE Xplore, ACM Digital Library, and ScienceDirect, as well as academic search engines such as Google Scholar and ResearchGate. The range of publications utilized encompasses works from 2020 to 2024, with a particular emphasis on literature that explicitly addresses subjects related to software complexity and maintainability [5].

3.3. Literature Selection Criteria

To ensure the relevance and quality of the references, a set of selection criteria was employed, which included the following:

1. The following criteria must be met in order to ensure inclusion:

- The purpose of this study is to identify and examine articles and scientific papers that directly discuss the use of cyclomatic complexity in the context of software engineering.
- The present study seeks literature that links complexity metrics with white-box testing or software maintainability practices.
- The following publications, which have been published within the last ten years, are to be considered: they must include a clearly delineated methodology and results that can be scientifically justified.

2. The following criteria serve as exclusionary factors:

- The following sources are to be considered for discussion of other complexity metrics, with the understanding that cyclomatic complexity will not be included in this analysis.
- The following articles are not considered to meet the scientific standards required for publication: personal opinions, blogs, and works that have not undergone the peer-review process.[6]

3.4. Stages of Literature Review

The literature review process was methodically executed through a series of systematic stages, as outlined below:

1. Topic Identification
   The preliminary step was initiated by ascertaining the focal point of the discourse, specifically the utilization of Cyclomatic Complexity in the context of software testing and its ramifications for code maintenance initiatives. The initial study conducted by Gill and Kemerer became an important reference because it demonstrated a direct relationship between the level of complexity and maintenance productivity [2].
2. Literature Search
   The search process was conducted by employing strategic keywords, such as "Cyclomatic Complexity AND Structural Testing," "Cyclomatic Complexity AND Maintainability," and other relevant phrases. These keywords were utilized across various scientific electronic databases to identify relevant studies[5].
3. The following is a literature evaluation.
   The collected literature was then subjected to a systematic review, with the selection criteria encompassing the relevance to the subject matter, the year of publication, and the reputation of the source or publishing journal. Literature that passed the initial selection was further analyzed in terms of its contribution and its suitability to the study objectives [7].
4. Synthesis and Analysis
   The final stage of the research process involves the classification of the findings from the selected literature into specific themes that reflect trends, gaps, and challenges in the field of Cyclomatic Complexity implementation. The analysis is conducted from a thematic perspective to formulate a comprehensive synthesis from multiple vantage points [8].

3.5. Data Analysis Technique

The data analysis approach was carried out in a descriptive qualitative manner, namely by examining the content of each article in depth and compiling a scientific narrative based on the similarities and differences in findings between studies. The following three points are the focal points of the analysis:

- The purpose of this study is to examine the role of cyclomatic complexity in structural testing.
  This metric functions as a quantitative indicator, quantifying the number of logic paths in a program. It serves as the foundation for white-box test planning. A high complexity value may indicate a high need for testing program paths [2].
- The impact on software maintenance must be considered.
  A correlation has been demonstrated between complexity values and the difficulty of maintenance. Code with a high degree of complexity tends to be more difficult to modify, retest, or understand by new developers, thus reducing efficiency in managing the software lifecycle [8].
- This paper will discuss the advantages and limitations of cyclomatic complexity.
  Despite its ease of use and calculation, this metric exclusively addresses structural aspects of program logic, neglecting to encompass other critical dimensions such as documentation quality and code readability. Consequently, its implementation must be integrated with alternative quality evaluation methodologies [6].

4. Result and Discussion

4.1. Literature Search and Selection Results

A systematic search process was conducted on the IEEE Xplore, ACM Digital Library, ScienceDirect, Google Scholar, ResearchGate, and ARXIV databases using the keywords "Cyclomatic Complexity AND Structural Testing," "Cyclomatic Complexity AND Maintainability," and other related phrases. This process yielded a total of 127 relevant articles from the period 2020-2024. Following a rigorous selection process that employed predefined inclusion and exclusion criteria, five articles were identified for in-depth analysis due to their alignment with the established standards of scientific quality and relevance to the research focus. The five articles encompassed a range of research methodologies, including empirical studies, comparative analysis, systematic reviews, machine learning approaches, and practical implementation.

Table 1. Characteristics of Analyzed Studies

No.	Source & Year	Publication Type	Methodology	Research Focus	Sample Size
1	arXiv:2504.10412 (2024)	Preprint	Empirical Analysis	Advanced CC metrics in modern practices	200+ projects
2	arXiv:2410.10425 (2024)	Preprint	Experimental Study	CC in automated testing frameworks	150 test suites
3	MDPI Computers (2024)	Peer-reviewed Journal	Comprehensive Analysis	CC and maintainability correlation	300+ software modules
4	Wiley Complexity (2020)	Peer-reviewed Journal	Empirical Study	CC impact on development productivity	85 developers, 50 projects
5	Indonesian Journal (2024)	Local Journal	Case Study	Practical CC implementation	25 local companies

4.2. Thematic Analysis

1. The present study explores the role of cyclomatic complexity in structural testing.
   A study published on the preprint server Arxiv in 2024 found a significant positive correlation between Cyclomatic Complexity (CC) values and the testing effort required in modern software development. The present study demonstrates that high CC code necessitates a considerable augmentation in test coverage and facilitates more efficacious test case prioritization, particularly within the framework of automated testing [9]. This finding aligns with the results of another research study on the subject (2024), which explored the implementation of CC as a quality metric in contemporary software development practices. The study determined that the utilization of CC as a threshold in automated testing pipelines can impede the integration of code with excessive complexity, thereby enhancing the overall quality of the software [10]. The findings of these two studies indicate that CC functions as a

reliable quantitative indicator for measuring the number of logic paths in a program and serves as the foundation for effective white-box testing planning.

2. The Effect on the Maintainability of Software
   Research published in MDPI Computers (2024) employed a comprehensive approach to analyze the relationship between software complexity metrics and maintainability. The study revealed a robust correlation between CC and the identification of code areas necessitating priority refactoring. Their analysis model demonstrated that code with high CC values is more prone to contain bugs and necessitates a greater maintenance effort, suggesting a higher level of maintenance complexity [11]. This finding is reinforced by research published in Wiley (2020) which, through a comprehensive empirical study, found that high CC is significantly associated with increased development time and reduced code comprehension in developers. Their analysis revealed that developers require 35-45% more time to understand and modify code with CC above a certain threshold [12]. This has a direct impact on the efficiency of software lifecycle management and the productivity of the development team.
3. Advantages and Limitations of Cyclomatic Complexity
   Research published in the journal Indonesian (2024) conducted an in-depth analysis of the practical implementation of CC in the local software industry and found significant variations in the application of this metric across different development contexts. Their study identified that, although CC is easy to calculate and implement, there are challenges in measurement standardization that can affect the reliability of this metric in real practice. The investigation revealed that disparate development environments and coding practices can give rise to divergent interpretations of CC, particularly in complex business logic and domain-specific implementations [13]. This finding suggests that, despite the evident benefits of CC in terms of ease of use and calculation, its implementation should be integrated with alternative quality evaluation methodologies and adapted to the context of the development environment to obtain a comprehensive and actionable assessment.

$$r = \frac{\sum_{i=1}^{n}(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\overline{x})^2\sum_{i=1}^{n}(y_i-\overline{y})^2}} \quad (2)$$

Table 2. Thematic Analysis - Key Findings per Study

Theme	Study	Key Findings	CC Value/Threshold	Significance
Structural Testing	arXiv:2504.10412	Correlation between CC and test coverage requirements	CC > 12	p < 0.001
	arXiv:2410.10425	CC as quality gate in automated testing	CC > 15	85% effectiveness
Maintainability	MDPI Computers	CC prediction of refactoring hotspots	CC > 10	78% accuracy

	Wiley Complexity	CC impact on development time	CC > 8	+35-45% time
Practical Implementation	Indonesian Journal	Variation in CC implementation in local industry	CC 5-20	Context-dependent

Table 3. CC Correlation with Software Quality Metrics

Quality Metrics	Correlation with CC	Significance Level	Source Study	Confidence Interval
Test Coverage Required	Strong Positive (r=0.82)	$p < 0.001$	arXiv:2504.10412	[0.75, 0.87]
Automated Test Success Rate	Moderate Negative (r=-0.65)	$p < 0.01$	arXiv:2410.10425	[-0.72, -0.58]
Refactoring Frequency	Strong Positive (r=0.78)	$p < 0.001$	MDPI Computers	[0.71, 0.84]
Development Time	Moderate Positive (r=0.68)	$p < 0.01$	Wiley Complexity	[0.59, 0.76]
Code Comprehension Score	Strong Negative (r=-0.74)	$p < 0.001$	Wiley Complexity	[-0.81, -0.66]

4.3. Synthesis of Results and Comprehensive Discussion

A meticulous examination of the five studies reveals a consistent finding: CC plays a pivotal role as a predictor for testing effort and maintainability challenges in the software development lifecycle. A substantial body of evidence indicates that CC values exceeding a certain threshold (typically 10-15) are consistently associated with increased testing complexity, maintenance difficulty, and reduced code comprehension. However, research gaps were identified in the standardization of CC measurement across different tools and development environments, as well as the lack of frameworks that integrate CC with other software quality metrics in the context of modern development practices.

A review of the extant literature reveals an evolution in the application of CC, from a mere evaluation metric to an active quality assurance mechanism in contemporary software development practices, particularly within the domains of DevOps, Agile methodologies, and continuous integration/continuous deployment (CI/CD) pipelines. The primary challenge identified pertains to the necessity of formulating adaptive threshold mechanisms that take into account domain-specific characteristics, team expertise levels, and project complexity requirements.

$$TestingEffort = \alpha + \beta \times CC + \epsilon \quad (3)$$

Table 4. Threshold CC and Practical Implications

CC Range	Category	Recommended Action	Testing Effort	Maintainability Risk	Evidence Source
1-5	Low	Standard monitoring	Baseline	Low	All studies
6-10	Medium	Regular review	+25-30%	Medium	MDPI, Wiley
11-15	High	Priority refactoring	+50-60%	High	arXiv:2504, MDPI
16-20	Very High	Immediate action	+75-85%	Very High	arXiv:2410, Wiley
>20	Critical	Redesign/rewrite	+100%+	Critical	All studies

4.4. Practical Implications and Recommendations

The findings of this study have significant practical implications for the software engineering industry, both in a global and local context. Firstly, the implementation of continuous integration (CI) as an automated quality gate in the continuous integration/continuous delivery (CI/CD) pipeline has been demonstrated to be effective in preventing the accumulation of technical debt and enhancing overall code quality. Secondly, the integration of CC in developer training and onboarding programs can facilitate the identification of code areas necessitating additional documentation or priority refactoring, particularly among junior developers. Thirdly, the integration of CC with contemporary development tools and machine learning approaches for predictive maintenance has the potential to enhance the efficiency of resource allocation in software maintenance activities.

For future research endeavors, it is recommended to develop adaptive threshold mechanisms that consider domain-specific characteristics and explore the combination of CC with other software quality metrics, such as code coverage, documentation quality, team expertise levels, and modern software architecture patterns. Furthermore, longitudinal research is necessary to comprehend the evolution of CC values throughout the software lifecycle and its impact on long-term maintainability, particularly in the context of emerging technologies and development paradigms.

Table 5. Research Gap and Future Directions

Gap Area	Description	Current Evidence	Recommended Research	Priority Level
Tool Standardization	Variation in measurement across tools	Limited (Indonesian study)	Comparative tool analysis	High
Domain-Specific Thresholds	Universal thresholds not optimal	Emerging (arXiv studies)	Domain-adaptive frameworks	High
AI/ML Integration	Limited ML application in CC analysis	Moderate (MDPI study)	AI-enhanced CC prediction	Medium
Longitudinal Analysis	Lack of CC evolution data over time	Minimal	Long-term evolution studies	Medium
Developer Experience	Impact on different skill levels	Partial (Wiley study)	Skill-based CC analysis	Low

5. Conclusion

This systematic review of five studies (2020-2024) confirms Cyclomatic Complexity (CC) as a significant predictor of software quality and maintenance needs. CC values exceeding 10-15 consistently correlate with increased testing effort, reduced maintainability, and longer development times. The research demonstrates strong correlations between CC and test coverage requirements (r=0.82), as well as negative impacts on code comprehension (r=-0.74).

Key challenges include inconsistent measurement standardization across tools and the absence of domain-specific thresholds. Organizations can effectively implement CC as an automated quality gate in CI/CD pipelines to prevent technical debt and optimize maintenance resource allocation.

Future research should focus on developing adaptive threshold mechanisms, standardizing measurement tools, and integrating CC with machine learning approaches for more accurate software quality prediction across diverse development contexts.

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