

LONG-TERM MAINTENANCE COST FORECASTING AND WARRANTY BUDGET PLANNING FOR RESIDENTIAL BUILDINGS IN BANGKOK, THAILAND

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Abstract

This study evaluates the adequacy of current warranty budget *allocations* in residential developments and proposes differentiated, data-driven percentages based on long-term maintenance cost projections and project characteristics. Empirical defect data from five condominium projects in Bangkok, varying in unit type, scale, and market positioning, were collected between 2019 and 2023 and used to model 30-year cost projections through linear regression. The findings show that maintenance costs consistently increase over time, with annual cost slopes ranging from USD 10,162 to USD 30,857 and R^2 values between 0.90 and 0.99, while projected lifetime maintenance costs represent 5.56% to 11.26% of total project values. The widely adopted 2% warranty allocation was found to be inadequate, depleting as early as year 11 in high-density or lower-cost projects. Based on cumulative cost behavior and project conditions, differentiated warranty budgets of 6% to 11% are recommended to ensure financial sustainability. While the analysis is limited to five projects in Bangkok and linear forecasting methods, the results underscore the importance of empirical, context-sensitive approaches to warranty planning. By integrating real defect data with long-term cost modeling, this research provides a practical framework for improving financial foresight, construction quality, and asset management in rapidly urbanizing regions.

Keywords: Budget planning; Defect analysis; Maintenance cost; Predictive maintenance modeling; Residential project; Warranty budget

Introduction

The quality and durability of residential construction play a critical role in determining long-term maintenance requirements and occupant satisfaction. While initial construction standards and material choices influence the frequency and severity of post-occupancy defects, effective

planning for warranty-related expenditures is essential for maintaining performance standards and minimizing financial risk. In many housing markets, particularly in rapidly urbanizing regions, developers allocate a fixed percentage of project value, which was commonly at 2% as a warranty

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reserve. However, such estimates are often based on industry norms rather than empirical data and may not reflect the actual long-term cost behavior of different project types. Existing literature on building lifecycle cost (AlJaber *et al.*, 2025; Nabawy *et al.*, 2025; Vázquez-López *et al.*, 2024; Zhou *et al.*, 2024) has emphasized the need for accurate forecasting tools to anticipate maintenance demands over time. Despite this, there remains a gap in practical data-driven models that align warranty budgeting with the real-world performance of residential developments in Bangkok, particularly those with varying unit densities, market positions, and construction quality. High-density projects, for example, may face accelerated wear and more frequent repairs, while high-end developments typically demand higher service standards and complex system maintenance. Mahpour (2023) emphasized that the maintenance phase remains underexplored despite its significant contribution to resource consumption and waste generation.

This study addresses this gap by analyzing five residential projects in Thailand, each with different characteristics in terms of unit configuration, land use intensity, and investment scale. Historical maintenance records from 2019 to 2023 were collected and analyzed to evaluate annual defect rates, cost of repairs, and total maintenance expenditures. Linear curve fitting was applied to model cost trends over a 30-year period, and the sufficiency of the 2% warranty budget was assessed across all cases. Comparative metrics, such as cost as a percentage of project value and the number of years until budget depletion, were used to propose more realistic budgeting strategies. The objective of this research is to evaluate the adequacy of current warranty budget allocations in residential developments and to propose differentiated, data-driven budget percentages based on long-term maintenance cost projections and project characteristics. In this specific context, the developer aimed to establish a sinking fund to support extended post-construction maintenance. All condominium units were sold with a strategic commitment to provide a 30-year warranty covering four key aspects: structural integrity, water leakage, electrical and plumbing systems, and door and window functionality. Accordingly, this study seeks to evaluate whether the conventional 2% sinking fund allocation is sufficient, determine if the fund would be depleted before the end of the 30-year period, and estimate the total funding required to sustain these long-term maintenance obligations for all units throughout the 30-year duration.

Literature Review

Warranty systems for residential buildings vary widely across countries. In the USA, home builders often provide free warranties ranging from one to ten years, while in Singapore, a minimum one-year warranty period is prescribed under the Housing Developers Rules (Ong, 1997). In Thailand, however, developers typically offer only a two-year warranty, after which unit owners or the condominium juristic person is responsible for maintenance. Sommerville (2008) highlighted that warranty systems in the UK, France, Japan, Australia, Canada, and the USA differ in coverage, structure, and consumer protection, with some countries adopting stricter legal frameworks and others relying on private providers. Such diversity results in varying standards for warranty systems and levels of consumer protection among these nations. Similarly, Royal *et al.* (2022, 2023) compared warranty schemes across multiple countries, emphasizing variations in financial sustainability, defect liability periods, and dispute resolution systems. These studies underscore the lack of a universally optimal model, highlighting the need for context-specific warranty frameworks that balance financial feasibility with consumer protection.

Defects during the warranty period represent a major driver of maintenance costs. Plebankiewicz and Malara (2020) analyzed three Polish residential buildings and found that owners were particularly active in reporting claims within the first three months after handover. Regarding costs, the study cites previous literature stating that repair costs typically account for 4-4.4% of the project value. Plebankiewicz *et al.* (2022) identified that maintenance cost estimation is multifaceted, driven by variables such as asset age, condition, necessary resources, and maintenance strategic approach. Long-term maintenance cost forecasting for residential buildings utilizes lifecycle models to predict expenses, while warranty budget planning allocates reserves for defects under standard 10-year structural warranties. Ultimately, balancing preventive strategies with reactive repairs shows that preventive maintenance is often the most cost-efficient approach over time. The study by Plebankiewicz *et al.* (2022) examines five distinct models via an office building case study: two focusing on rapid indicative budgeting, two incorporating discounted cash flows, and one aligned with Polish statutory standards. These models establish a critical framework for early-stage

planning. Ultimately, the choice of methodology must align strategically with both data quality and specific institutional objectives. In Korea, Park and Seo (2017, 2022, 2023) demonstrated that defects are concentrated within the first two to four years of occupancy, with average repair costs (0.538% of construction costs) being significantly lower than mandated warranty deposits, suggesting inefficiencies in policy design. Le *et al.* (2018) argue that the primary challenge in maintenance budget management is not a lack of forecasting models, but rather a deficiency in reliable historical data. Consequently, they propose a framework for the continuous storage of building condition data to support life-cycle cost (LCC) analysis over a 30-to-60-year horizon. By leveraging empirical building data, Jung *et al.* (2022) introduced a segmented budget forecasting model planned to assist government agencies in achieving sustainable, age-based maintenance management. Assaf *et al.* (1996) categorize major design and construction defects in Saudi Arabian large buildings and evaluate their relative severity. Significantly, faulty design, substandard materials, and inadequate waterproofing are identified as primary cost drivers, while Zalejska-Jonsson and Hungria-Gunnelin (2019) showed that building construction quality differs by developer size, and that location significantly influences the occurrence of defects in Sweden. Collectively, these studies emphasize the link among design quality, defect frequency, and long-term financial sustainability.

Recent advances in forecasting methods have sought to improve the accuracy of maintenance cost predictions. Li and Guo (2012) demonstrated the effectiveness of back-propagation artificial neural networks (BPN) in predicting long-term costs. By analyzing 42 years of historical maintenance and repair data from university buildings in Taiwan, their BPN model outperformed traditional regression models, providing a robust framework for establishing optimal life-cycle maintenance scenarios. Mazzetto (2025) compared six machine learning models, including Artificial Neural Networks (ANN), Random Forest (RF), Extreme Gradient Boosting (XGBoost), Support Vector Machine (SVM), K-Nearest Neighbors (KNN), and Logistic Regression (LR), by utilizing a high-resolution fault dataset from building HVAC, lighting, and occupancy systems, which resulted in over 100,000 fault instances. The findings showed that XGBoost outperformed the other models, achieving 95% accuracy and 93% precision. The model demonstrated strong fault detection capabilities, particularly regarding occupancy-related inefficiencies such as lighting and damper misuse. This study highlights how data-driven

approaches can improve long-term cost forecasting, reduce energy waste, and enhance operational efficiency. The integration of such predictive tools supports the development of more accurate maintenance planning frameworks, reinforcing the need for differentiated, evidence-based warranty budgeting in residential projects. Park *et al.* (2019) applied probabilistic analysis and Monte Carlo simulations to 224 multi-family housing units in South Korea aged 20 years or older. Their findings reveal that unplanned maintenance often accelerates long-term costs, demonstrating that probabilistic modeling serves as a vital tool for determining reasonable maintenance budgets and coping with the natural aging of residential properties. More recently, Abuhussain and Baghdadi (2024) developed a framework for predicting maintenance and operation costs in construction projects by integrating an emotional artificial neural network (EANN). This model outperformed conventional artificial neural network models in forecasting accurate long-term maintenance costs, reducing budgeting uncertainty, and enhancing management decision-making. Bouabdallaoui *et al.* (2021) proposed an IoT-based deep learning framework for HVAC predictive maintenance, validated through a sports facility case study. While the five-step methodology spanning data collection to system improvement effectively predicted failures, implementation was hindered by data scarcity and inconsistent feedback collection. Sala *et al.* (2024) further demonstrated the value of agent-based simulation in quantifying the long-term cost implications and productivity across various maintenance policies, utilizing key maintenance indices to help companies select the optimal strategy. The durability and performance of building materials are pivotal determinants of both maintenance costs and warranty adequacy. Urlainis *et al.* (2024) found that gypsum board partitions, while cost-effective, deteriorate rapidly under intensive conditions and require replacement within 11-27 years; by comparison, hollow concrete blocks can last over a century under light or moderate conditions. This contrast underscores the necessity of aligning material selection with both occupancy intensity and expected service conditions. Balasbaneh *et al.* (2025) conducted a systematic review of building refurbishment, renovation, and repair studies, identifying notable inconsistencies in cost evaluation while calling for multi-objective assessment methods that integrate both economic and environmental factors. These insights reinforce the need for differentiated budgeting, which accounts for material durability, user behavior, and broader sustainability metrics. Beyond these technical considerations, organizational and cultural

factors also fundamentally shape long-term maintenance outcomes. Furthermore, Zeni and Kikwasi (2023) validated these findings, identifying building age, deficient quality control, and fiscal constraints as primary cost drivers. Their analysis uncovers a stakeholder divergence: whereas tenants prioritize resource management, experts emphasize technical failures such as material misuse and faulty maintenance. Consequently, public housing expenditures are dictated by building senescence and the recurring burden of reactive, urgent repairs. Desbalo *et al.* (2024) studied facility maintenance management (FMM) in Ethiopian public universities and identified four critical factors affecting FMM effectiveness: (1) internal processes and organization, (2) community culture, learning, and growth, (3) the impact of design and construction quality, and (4) facility maintenance approach and management. They highlight the immaturity of FMM practices in underdeveloped contexts. The study concludes that transitioning from reactive to proactive, data-driven maintenance significantly improves building performance and sustainability. These findings further demonstrate that this effectiveness requires not only technical forecasting but also institutional support, aligning with the need for project-specific considerations in the warranty budget planning.

The reviewed literature demonstrates three important themes relevant to this research: firstly, warranty practices and policies are highly diverse and often misaligned with actual defect and cost behaviors; secondly, empirical evidence consistently shows that design quality, construction materials, and occupancy intensity strongly affect defect rates and long-term maintenance costs; and thirdly, recent advances in lifecycle cost forecasting offer improved accuracy but are rarely applied to warranty budgeting in residential developments. At the same time, organizational and contextual factors also shape maintenance efficiency, further reinforcing the need for differentiated approaches. Despite these advances, few studies have combined real defect data from operating residential projects with long-term cost forecasting to evaluate warranty adequacy. This gap underpins the objective of the present study: to analyze empirical defect and cost data from condominium projects in Bangkok, develop 30-year maintenance cost projections using linear regression, and propose differentiated, data-driven warranty budget allocations that better reflect project typology, quality, and usage conditions.

Methodology

This study adopted a data-driven approach to evaluate long-term maintenance costs and determine appropriate warranty budget allocations for residential developments. Actual defect data were collected from five condominium buildings developed by a single real estate company in Bangkok, Thailand. All five projects are condominium developments by the same developer. This study employed a multiple case study approach focusing on this developer under a warranty framework covering four key aspects. Therefore, the findings may not be generalized to serve as guidance for other developers. The data included the annual number of reported defects, associated repair costs, and total expenditures incurred during the warranty period. All financial figures in this study are reported in nominal terms, representing the actual expenditures recorded in each respective year without adjustment for inflation. To ensure international comparability, currency conversion from Thai Baht (THB) to United States Dollars (USD) was performed using the annual average exchange rate observed during the data collection period. The developer provides a comprehensive warranty covering four key aspects: structural integrity, water leakage, electrical and plumbing systems, and door and window functionality. Accordingly, the study was framed within a 30-year planning horizon to reflect the intended coverage period. The five buildings under investigation vary in operational lifespan: one project has been in operation for five years, two for four years, and the remaining two for three years. The maintenance cost records from these buildings formed the empirical basis for model development. For each project, annual maintenance costs were analyzed, and linear trend lines were fitted to estimate future expenditures. The slope of each cost trend was determined through linear regression, with reliability assessed through the coefficient of determination (R^2). These cost slopes were then extrapolated to estimate cumulative maintenance costs over a 30-year period. To facilitate a fair comparison across projects of varying investment sizes and scales, all costs were normalized as a percentage of the total project value. The study also evaluated the sufficiency of the industry-standard 2% warranty budget by identifying the year in which each project would fully deplete this allocation. Based on observed cost behavior and long-term projections, this research proposed differentiated

warranty budget percentages tailored to project characteristics. By integrating empirical data, linear forecasting, and comparative analysis, this methodology provides a robust framework for assessing lifecycle maintenance demands and informing more realistic and sustainable warranty budgeting strategies in residential development. Table 1 provides financial data for five condominium development projects, detailing their land area, number of residential units, total project value, and allocated maintenance budgets. Project A consists of 497 residential units. The total project value is estimated at USD 82,801,160, with an allocated maintenance budget of USD 1,656,023. Similarly, Project B comprises a larger total of 690 residential units. Its total project value is approximately USD 79,991,491, with an allocated maintenance budget of USD 1,599,830. Each residential project differs in terms of size, unit density, and construction quality. For example, as shown in Table 1, Project B exhibits the highest population density, whereas Project D is the most sparsely populated when comparing land area relative to the number of residential units. Project C comprises 673 residential units, with a total project value of USD 97,034,922 and an allocated maintenance and repair budget of USD 1,940,698. Meanwhile, Project D consists of 664 residential units. It possesses the highest project value among the five developments, totaling USD 137,460,327, and features the largest allocated maintenance budget of USD 2,749,207. Project E contains 554 residential units and has a total project value of USD 95,905,948, with a maintenance budget of USD 1,918,119. As indicated in Table 1, the developer has set the maintenance budget for each project at 2% of its total value.

Table 2 presents the number and cost of defects incurred across five condominium projects over their operating period. It provides insights into the distribution of maintenance expenses, trends over time, and variations between different projects. Analyzing these figures helps identify patterns in maintenance spending, potential cost drivers, and the financial impact of different maintenance strategies.

In addition to variations in unit type and project value, an examination of building age and defect records offers critical insights into long-term warranty performance and construction quality. As presented in Table 2, the five projects under study have been in operation for varying durations. Data were collected from 2019 to 2023. Over these periods, Project B reported the highest number of defects, with 1,373 cases over four years, yielding an average of approximately 343 defects per year, as presented in Table 3. Project A followed with 1,254 defects over a five-year span, averaging 251 defects annually. Despite its shorter operational life, the relatively higher annual defect rate in Project B may be attributed to the smaller, one-bedroom unit configuration and higher occupancy density, as the development is targeted toward working-class residents, potentially resulting in more intensive use and accelerated wear.

In contrast, Project D, which comprises larger two-bedroom units and has been operating for three years, recorded 786 defects, which translates to an average of 262 defects per year, representing a moderate rate. This may reflect its superior construction quality and lower unit density. Project C, which has also been in operation for four years, registered 610 defects, representing 153 defects

Table 1. Project characteristics and allocated warranty budgets

Project	Land Area, m ²	Number of Residential Units	Type of Residential Buildings	Total Project Value, \$	Allocated Warranty Budget at 2% of Project Value, \$
A	4,800	497	Mid-Range	82,801,160	1,656,023
B	4,800	690	Affordable	79,991,491	1,599,830
C	8,000	673	Mid-Range	97,034,922	1,940,698
D	9,600	664	High-End	137,460,327	2,749,207
E	8,000	554	High-End	95,905,948	1,918,119

Table 2. Annual number and cost of defects by project

Year	Project A		Project B		Project C		Project D		Project E	
	Number of Defects	Cost of Defects, \$	Number of Defects	Cost of Defects, \$	Number of Defects	Cost of Defects, \$	Number of Defects	Cost of Defects, \$	Number of Defects	Cost of Defects, \$
2019	514	24,235	-	-	-	-	-	-	-	-
2020	105	28,427	265	35,678	233	32,405	-	-	-	-
2021	133	34,777	207	46,969	79	46,860	201	25,149	309	27,562
2022	231	65,318	231	64,056	100	57,358	150	68,938	186	46,134
2023	271	79,222	670	90,857	198	62,779	435	86,863	93	67,497
Total	1,254	231,979	1,373	237,560	610	199,402	786	180,950	588	141,193

Table 3. Summary of operational years, defect frequency, and warranty cost utilization

Project	Operating Years	Average Number of Defects per Year	Average Annual Cost of Defects, \$	Total Cost of Defects, \$	Percentage of Allocated Warranty Budget Utilized
A	5	251	46,396	231,979	14%
B	4	343	59,390	237,560	15%
C	4	153	49,851	199,402	10%
D	3	262	60,317	180,950	7%
E	3	196	47,064	141,193	7%

Table 4. Maintenance cost summary, warranty budget allocation, and cost trend analysis

Items	Project A	Project B	Project C	Project D	Project E
Total Maintenance cost incurred, \$	231,979	237,560	199,402	180,950	141,193
Provided Warranty Budget, \$	1,656,023	1,599,830	1,940,698	2,749,207	1,918,119
Actual Maintenance Cost (% of Project Value)	0.28%	0.30%	0.21%	0.13%	0.15%
Remaining Budget, \$	1,424,044	1,362,270	1,741,296	2,568,257	1,776,926
Annual Cost Slope, \$	14,687	18,262	10,162	30,857	19,968
R ²	0.90	0.97	0.96	0.95	0.99

Note: All financial figures are presented in nominal USD, converted from THB based on the annual average exchange rates observed during the reporting period.

annually. Meanwhile, Project E reported 588 defects over three years, averaging 196 defects per year.

The percentage of the allocated warranty budget for project A in Table 3 is calculated by dividing the cost of defects by the allocated warranty budget from Table 1. Projects A and B stand out with significantly high warranty budget consumption, utilizing 14% and 15% of their allocated budgets, respectively. The increased usage in these two projects may be attributed to factors such as building age, smaller unit sizes, and higher unit density, all of which contribute to a higher frequency of defects and maintenance demands.

In contrast, Project C utilized 10% of its allocated warranty budget over a four-year period, despite reporting a relatively low number of annual defects. This indicates that while the defect frequency was lower, the average cost per defect was consistently higher. This is potentially due to the complexity or specialized nature of the repairs required.

Meanwhile, Projects D and E demonstrated more efficient warranty budget performance, each consuming only 7% of their respective budgets. Although their service life spans just three years, Project D recorded the highest annual cost of defects among all projects. This is reflected in an average annual cost of defects amounting to USD 60,317, as presented in Table 3. This can be attributed to its classification as a high-end development, where the maintenance of premium materials and systems typically incurs higher repair costs, even when defect frequency remains moderate.

Results of the Study

Analysis of maintenance costs across the five projects

Table 4 shows maintenance costs as a percentage of project value and the remaining budget. When examining the actual cost as a percentage of the total project value, all projects remain within a narrow range, from 0.13% for Project D to 0.30% for Project B, reflecting modest warranty-related expenditures relative to the overall investment. However, when viewed against the allocated warranty budgets, distinct patterns emerge.

The linear curve fitting process in this study began with the collection of actual annual maintenance cost data for each residential project over their respective operational years. The observed annual maintenance cost values were plotted against time to illustrate year-on-year trends, as indicated by the individual data markers in Figures 1 to 5. Linear regression analysis was subsequently applied to each dataset to generate the best-fit line, representing the relationship between maintenance cost and time, as shown by the dotted lines in the figures, which represent the fitted linear regressions derived from empirical data and serve as the basis for the cost projection. The slope of each line represents the annual cost slope, indicating the rate at which maintenance costs increase over time. Additionally, the coefficient of determination (R²) was calculated to evaluate the goodness-of-fit and reliability of the linear model, confirming its suitability for projecting long-term maintenance expenditures.

Maintenance cost trends

Based on the defect cost trend figures and curve fitting analysis for Projects A through E, all developments exhibit a clear upward trajectory in annual maintenance costs, though the rate of increase varies by project type and quality. Project A, operating since 2019, shows a moderate slope of USD 14,687 per year with an R^2 of 0.90, indicating a reliable linear increase in costs consistent with building aging, as shown in Figure 1.

Project B, which serves working-class residents with one-bedroom units, demonstrates a steeper annual cost increase of USD 18,262, with a strong R^2 of 0.97, suggesting high usage intensity, as illustrated in Figure 2.

Project C, a moderate-tier project, has the lowest annual cost slope of USD 10,162 and an R^2 of 0.96, indicating a slower, stable increase in defect costs and potentially more efficient system performance or fewer maintenance-intensive components (Figure 3).

In contrast, Project D, a high-end development with two-bedroom units, shows the highest rate of annual cost escalation at USD 30,857, with an R^2 of 0.95, as presented in Figure 4. This rapid growth is

reflective of the higher expectations, complexity, and long-term servicing needs associated with premium developments.

Project E, also of moderate quality, shows a consistent rise of USD 19,968 per year, with an R^2 value of 0.99, indicating a nearly linear trend across the observed period (Figure 5).

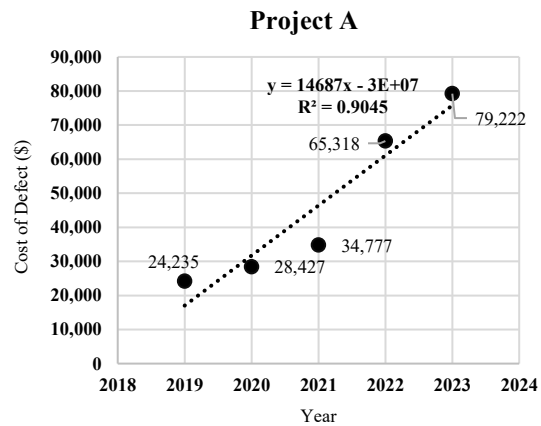


Figure 1. Maintenance costs during the first five years of Project A

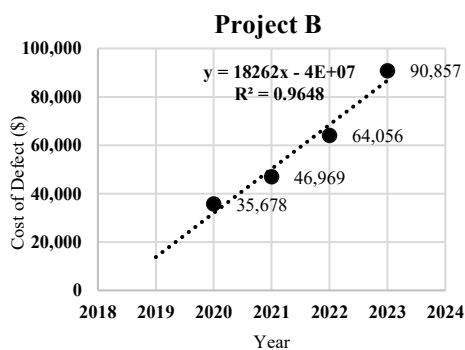


Figure 2. Maintenance costs during the first four years of Project B

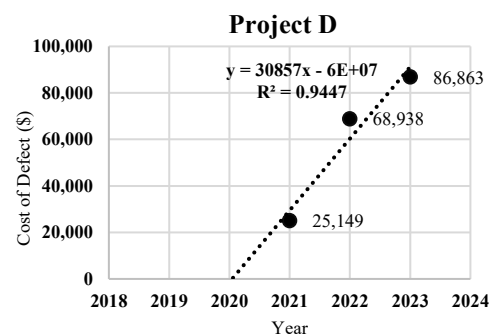


Figure 4. Maintenance costs during the first three years of Project D

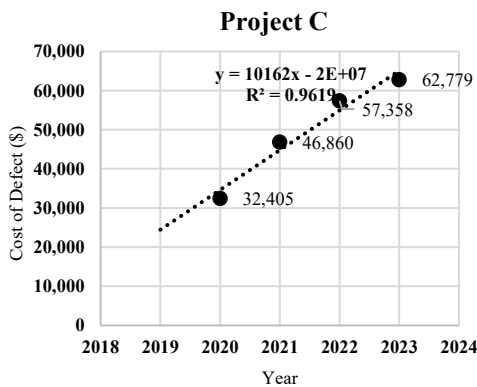


Figure 3. Maintenance costs during the first four years of Project C

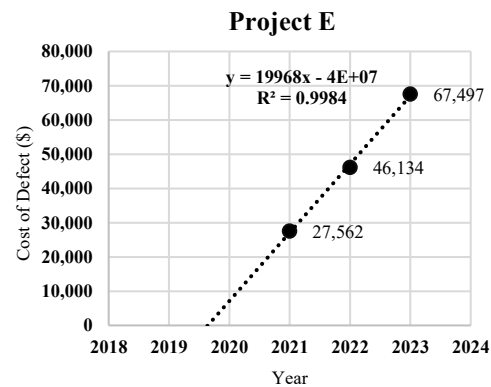


Figure 5. Maintenance costs during the first three years of Project E

Table 5 shows thirty-year projected maintenance costs for five residential projects, with a focus on comparing long-term expenditures as a percentage of total project values, enabling equitable benchmarking across developments of varying scales. During the first five years, the data presented in Table 5 were derived directly from the actual values in Table 2. For subsequent years, the projected data were generated by cumulatively applying the annual cost slope from Table 4 to estimate maintenance expenses over time.

When normalized by project value, Project B demonstrates the highest long-term maintenance cost burden, with thirty-year accumulated costs representing 11.26% (approximately 11%) of its USD 79.99 million project value. Despite its working-class positioning and smaller unit design, this result suggests either a high frequency of repair needs or more intensive wear-and-tear per unit area. This highlights developments of similar demographic and typology. Project D, though incurring the highest absolute maintenance cost of

USD 14.19 million, represents 10.32% (approximately 10%) of its USD 137.46 million project value. This aligns with expectations for a high-end development, where more complex building systems, luxurious finishes, and higher occupant expectations drive long-term maintenance obligations. Project E incurs maintenance costs equal to 10% of its USD 95.91 million value, while Project A performs slightly better at 8.44% (approximately 8%) of its USD 82.80 million value. These percentages suggest a balanced maintenance cost profile consistent with construction standards and average defect rates. Remarkably, Project C, which is a moderate-scale project with a total value of USD 97.03 million, exhibits the lowest long-term maintenance ratio, at 5.56% (approximately 6%) over thirty years. This suggests superior construction quality on the part of contractors, efficient spatial planning, and the use of fewer costly systems, making it a cost-effective model for long-term sustainability.

Table 5. Projected annual maintenance costs over a 30-year period and recommended warranty budget proportions

Years	Project A	Project B	Project C	Project D	Project E
1	24,235	-	-	-	-
2	28,427	35,678	32,405	-	-
3	34,777	46,969	46,860	25,149	27,562
4	65,318	64,056	57,358	68,938	46,134
5	79,222	90,857	62,779	86,863	67,497
6	93,909	109,119	72,941	117,720	87,465
7	108,596	127,381	83,103	148,577	107,433
8	123,283	145,643	93,265	179,434	127,401
9	137,970	163,905	103,427	210,291	147,369
10	152,657	182,167	113,589	241,148	167,337
11	167,344	200,429	123,751	272,005	187,305
12	182,031	218,691	133,913	302,862	207,273
13	196,718	236,953	144,075	333,719	227,241
14	211,405	255,215	154,237	364,576	247,209
15	226,092	273,477	164,399	395,433	267,177
16	240,779	291,739	174,561	426,290	287,145
17	255,466	310,001	184,723	457,147	307,113
18	270,153	328,263	194,885	488,004	327,081
19	284,840	346,525	205,047	518,861	347,049
20	299,527	364,787	215,209	549,718	367,017
21	314,214	383,049	225,371	580,575	386,985
22	328,901	401,311	235,533	611,432	406,953
23	343,588	419,573	245,695	642,289	426,921
24	358,275	437,835	255,857	673,146	446,889
25	372,962	456,097	266,019	704,003	466,857
26	387,649	474,359	276,181	734,860	486,825
27	402,336	492,621	286,343	765,717	506,793
28	417,023	510,883	296,505	796,574	526,761
29	431,710	529,145	306,667	827,431	546,729
30	446,397	547,407	316,829	858,288	566,697
31	-	565,669	326,991	889,145	586,665
32	-	-	-	920,002	606,633
Thirty Years Accumulation	6,985,804	9,009,804	5,398,518	14,190,197	9,511,516
Total Project Values	82,801,160	79,991,491	97,034,922	137,460,327	95,905,948
Recommended Warranty Budget	8.44%	11.26%	5.56%	10.32%	9.92%
(% of Project Value)	(8.00%)	(11.00%)	(6.00%)	(10.00%)	(10.00%)

Based on these findings, this study recommends warranty budget *allocations* for future developments ranging between 6% and 11% of the total project value. Projects with compact, budget-conscious designs targeting working-class segments may require higher reserves of 11%, while simpler or more efficient configurations may remain sustainable with a 6% to 8% allocation. High-end developments are advised to set aside around 10% of the total cost for warranty support to ensure long-term service quality. The analysis of warranty budget depletion timelines, based on a fixed allocation of 2% of the total project value, reveals considerable variability among the five residential developments, highlighting significant implications for long-term financial planning. According to current cost projections, Project B, which consists of affordable one-bedroom units targeted at the working-class segment, is projected to deplete its allocated warranty budget by year 11, which is the earliest among all projects, as presented in Table 6. This early depletion reflects the relatively high long-term maintenance burden for lower-cost developments, where higher defect rates or more intensive usage may increase repair frequency.

Table 6. Years until depletion of warranty budget allocated at 2% of project value

Project	Years of Budget Sufficiency
A	14
B	11
C	17
D	13
E	13

Projects D and E, both high-end developments featuring two-bedroom units, follow closely, with their warranty budgets becoming fully depleted by year 13. Despite their premium positioning, the elevated expectations for service quality and the presence of more complex building systems likely contribute to higher long-term maintenance expenditures, thereby shortening the effective duration of budget sufficiency. Project A, categorized as a moderate-standard development, sustains its warranty budget through year 14, suggesting slightly better long-term cost performance. Remarkably, Project C demonstrates the most favorable outcome, maintaining its 2% warranty allocation until year 17. This superior performance may be attributed to several factors, including high-quality material selection, efficient design, and superior construction workmanship on the part of contractors, making it a model for cost-efficient residential planning. Overall, the findings underscore that a 2% warranty budget is insufficient

to cover long-term maintenance obligations for most residential projects beyond the first 11 to 17 years, depending on typology and quality.

Conclusions and Recommendations

This study examined long-term maintenance cost trends across five residential projects in Bangkok, using actual defect data from the initial years of operation. The projects varied in size, density, unit configuration, and construction quality. For instance, Project B is the most densely populated, while Project D is the most sparsely populated when assessed by land area per unit. Despite these differences, all projects showed a consistent increase in maintenance costs over time, with annual cost slopes ranging from USD 10,162 to USD 30,857. The rate of cost escalation was most pronounced in high-density, working-class housing and high-end developments, both of which exhaust their 2% allocated warranty budgets within 11 to 13 years. In contrast, moderately designed projects such as Project C demonstrated greater cost efficiency, maintaining sufficient warranty reserves for up to 17 years. These findings suggest that operational age alone does not determine maintenance burden. Instead, project typology, construction quality, and usage intensity are critical factors. This aligns with Urlainis *et al.* (2024), who noted that occupancy intensity significantly influences the performance of building materials. When benchmarked against international standards as shown in Table 7, the inadequacy of Thailand's 2% allocation is consistent with evidence from Poland (Plebankiewicz & Malara, 2020), where actual repair costs demand 4-4.4% of the project value, and from Korea, where mandatory deposits are higher than the actual repair costs of 0.538% of construction costs (Park and Seo, 2022). In comparison, countries such as the USA and Singapore rely on contract-specific or minimum legal coverages, effectively shifting long-term costs to owners sooner (Ong, 1997). Against this backdrop, Bangkok's experience illustrates the broader pattern that low statutory allocations are systematically insufficient for real-world maintenance requirements. The study concludes that the conventional 2% warranty budget *allocation* is insufficient to meet long-term maintenance demands. It recommends a differentiated budgeting approach, with warranty reserves ranging from 6% to 11% of project value, depending on the building's complexity, quality, and target demographic. Regarding design quality, this aligns with Zalejska-Jonsson and Hungria-Gunnelin (2019) and Zeni and Kikwasi (2023) concerning efficient quality control.

Table 7. Illustrative contextual comparison of international warranty practices and specific maintenance cost indicators (coverage duration, typical allocation costs, and the notes & observations)

Country / Study	Coverage Duration	Typical Allocation / Costs	Notes & Observations
USA (Ong, 1997)	1-10 years	Not fixed %; contract-based	Short-term for finishes, long-term for structure
Singapore (Ong, 1997)	Minimum 1 year	No % specified	Statutory minimums were maintained by ownership and management post-implementation.
Thailand (Industry norms observed)	2 years	2% of project value	Common industry norms: insufficient long-term coverage.
Poland (Plebankiewicz & Malara, 2020)	5 years	4-4.4% of project value	Observed repair costs exceed Thailand's 2% norm
Korea (Park & Seo, 2022)	2-4 years (most defects occur)	0.538% of construction cost	Mandated deposits higher than actual repair costs
This Study – Bangkok (2025)	30-year (proposed)	6-11% of project value (recommended warranty budget)	Based on empirical defect data; 2% depletion rate within the 11-17 year range

Note: This table provides an illustrative contextual comparison of international warranty practices and specific maintenance cost indicators rather than a strict benchmark. Readers should exercise caution when comparing these figures directly.

It also supports the findings of Desbalo *et al.* (2024) on the impact of design and construction quality. Specifically, high-end and high-density developments should receive higher allocations, while standard or moderate projects may require less. Integrating cost forecasting techniques, such as linear curve fitting and annual cost slope analysis, into the early planning phase is an alternative for estimating the warranty budget and supporting long-term financial sustainability. This study proposed three key recommendations: First, quality control measures during construction should be strengthened in future projects to minimize maintenance costs over the service life of condominiums. Second, components associated with high maintenance costs should be systematically investigated and incorporated as key inputs in building and architectural design for future developments. Third, for ongoing projects, the findings provide critical insights for management in assessing whether the conventional 2% sinking fund for post-construction maintenance is adequate. Ultimately, the study concludes that the traditional 2% warranty budget allocation is insufficient to meet long-term maintenance demands and recommends a differentiated budgeting approach, with warranty reserves ranging from 6% to 11% of the total project value, which depends on construction quality and design effort. This also aligns with Desbalo *et al.* (2024), who found that proactive, data-driven maintenance significantly improves building performance and sustainability. Similarly, Balasbanch *et al.* (2025) argued that such practices fundamentally shape long-term maintenance outcomes. This is further supported by Jung *et al.* (2022), who introduced a segmented budget forecasting model to assist government agencies in achieving sustainable, age-based

maintenance management. These perspectives also relate to the work of Plebankiewicz *et al.* (2022) regarding asset age, condition, necessary resources, and strategic maintenance approaches for long-term cost forecasting.

For real estate developers, the findings underscore the importance of proactive decision-making in areas such as high-quality material selection, efficient architectural design, and the appointment of reputable, skilled contractors. By embedding these strategies into the initial stages of project development, stakeholders can ensure consistent service quality, reduce the risk of premature warranty budget depletion, and promote more sustainable and cost-effective management of residential assets throughout the building lifecycle.

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Author Contributions

Wannawit Taemthong: Conceptualization, methodology, validation, supervision, project administration, funding acquisition, and writing – review and editing.

Nattasit Chaisaard: Validation, writing – review and editing, and corresponding author responsibilities.

Wichai Cheyaphong: Investigation, data collection, methodology, validation, and interpretation of results.

All authors have reviewed and approved the final version of the manuscript and agreed to be accountable for the accuracy and integrity of the work.

Ethics Approval and Consent to Participate

This study used historical maintenance and defect-cost records obtained from five condominium projects developed by a single real estate company. The research did not involve experiments with human participants, interviews, surveys, medical information, or personally identifiable data. The project and company information was anonymized, and the findings are reported only in an aggregated form.

Formal ethics approval and informed consent from participants were therefore not sought because the study was based exclusively on anonymized organizational records and did not constitute human-participant research. Permission to use the records for academic research was obtained from the organization providing the data, and all information was handled in accordance with its confidentiality requirements.

Declaration of Generative AI Use

During the preparation and revision of this manuscript, the authors used ChatGPT, developed by OpenAI, to assist with English-language editing, initial grammatical correction, and improvements in clarity and academic style. However, this manuscript was finally proofread and edited for correctness in English language usage, including grammar, punctuation, spelling, and overall style, by a native English speaker with an academic background to ensure clarity and coherence.

Generative AI was not used to collect data, perform statistical analyses, generate research findings, or formulate the conclusions. All AI-assisted text was critically reviewed, revised, and verified by the authors, who take full responsibility for the accuracy, originality, and integrity of the published content.

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