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FLEET MANAGEMENT OF ROAD CONSTRUCTION EQUIPMENT

A Life-Cycle Costing Approach

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I dedicate this thesis to their memory, with gratitude for the influence they had on my professional journey.

RESUMO

Um activo pode continuar operacional mesmo quando já deixou de gerar valor económico suficiente. Esta dissertação desenvolve uma metodologia de gestão de activos e de apreciação de investimentos, baseada em dados, destinada a identificar esse momento em frotas de equipamento de construção rodoviária.

Com base na experiência prática de gestão de frotas, o estudo combina engenharia civil, análise financeira e custos do ciclo de vida para avaliar de que modo a idade dos equipamentos, a utilização, os encargos de manutenção, as paragens, o consumo de combustível e o valor residual influenciam o desempenho dos activos e o custo de posse. Os dados históricos da frota são convertidos em indicadores de decisão e analisados através do valor actual, do custo anual equivalente, da análise de sensibilidade e da simulação estocástica pelo método de Monte Carlo.

Os modelos desenvolvidos e os painéis de controlo em Power BI apoiam decisões de investimento relativas à manutenção, conservação, substituição ou renovação dos equipamentos. A metodologia relaciona o desempenho técnico com as suas consequências financeiras, permitindo às empresas de construção e aos proprietários de activos avaliar os custos do ciclo de vida, comparar alternativas, identificar necessidades de capital e melhorar a afectação de recursos.

A dissertação demonstra como os dados operacionais das frotas podem reforçar a gestão de activos e a apreciação de investimentos, tornando as decisões relativas aos equipamentos mais transparentes, fundamentadas e financeiramente defensáveis. Embora centrada em equipamentos de construção rodoviária, a abordagem pode ser adaptada a outros portefólios de infra-estruturas e activos de capital.

Palavras-chave: gestão de activos, análise de investimentos, custos do ciclo de vida, gestão de frotas, custos do ciclo de vida, apoio à decisão, Power BI

ABSTRACT

An asset can remain operational even after it has ceased to generate sufficient economic value. This thesis develops a data-driven asset-management and investment-appraisal framework for identifying that point in road-construction equipment fleets.

Drawing on practical fleet-management experience, the study combines civil engineering, financial analysis, and life-cycle costing to evaluate how equipment age, utilization, maintenance expenditure, downtime, fuel consumption, and residual value affect asset performance and ownership cost. Historical fleet data are transformed into decision indicators and assessed through present-value analysis, equivalent annual cost, sensitivity analysis, and stochastic simulation using Monte Carlo methods.

The resulting models and Power BI dashboards support investment decisions concerning whether equipment should be maintained, retained, replaced, or renewed. The framework connects technical performance with financial consequences, enabling contractors and asset owners to assess life-cycle costs, compare alternatives, identify capital requirements, and improve resource allocation.

The thesis demonstrates how operational fleet data can strengthen asset management and investment appraisal by making equipment decisions more transparent, evidence-based, and financially defensible. Although focused on road-construction equipment, the approach can be adapted to other infrastructure and capital-asset portfolios.

Keywords: asset management, investment appraisal, road-construction equipment, life-cycle costing, fleet management

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1 INTRODUCTION

1.1 CONTEXT AND MOTIVATION

Civil engineering plays a central role in economic and social development by ensuring the design, construction, and maintenance of infrastructure that supports the movement of people and goods, including roads, bridges, and highways (Peurifoy & Schexnayder, 2002). Among the resources required to deliver such infrastructure, construction equipment is a critical factor, both in terms of productivity and in terms of investment and operating costs over its life cycle (Gransberg & Rueda, 2020; Gransberg, 2015).

In road-construction projects, technical and economic performance depends strongly on the availability, reliability, and suitability of the equipment fleet, from earthmoving machines to compaction and paving equipment (Gransberg & Rueda, 2020). The intense competition in the construction sector, combined with chronically low profit margins, makes fleet-management optimization a vital element of a construction company's economic sustainability (Gransberg & Rueda, 2020). The need for higher operational efficiency and more rational investment decisions therefore requires robust decision-support tools based on life-cycle costing (LCC) principles (Fuller & Petersen, 1995; Park, 2011).

For this reason, methodologies that improve fleet planning and replacement decisions are particularly relevant, as they must account for equipment acquisition, operation, maintenance, and disposal costs, while also considering the risks and uncertainties associated with real construction-site conditions (Gransberg, 2015; O'Connor, 2014).

In this context, the main objective of this dissertation is to develop and implement a more systematic approach to equipment management in road-construction projects based on LCC models.

1.2 Transportation Infrastructure and Road Construction Equipment Investments

The execution of transportation infrastructure is heavily mechanized and relies on sophisticated construction equipment, such as excavators, bulldozers, motor graders, compaction rollers, and pavers. These assets are capital-intensive, both to purchase and to maintain (Peurifoy & Schexnayder, 2002). They also represent a substantial share of construction companies' investments, with ownership and operating costs often accounting for a significant portion of total road-project expenses (Gransberg & Rueda, 2020; Gransberg, 2015).

Appropriate fleet selection and sizing directly affect work-front productivity, project schedules, and final product quality, including pavement surface durability (Peurifoy & Schexnayder, 2002; Gransberg & Rueda, 2020). Decisions concerning purchase, rental, or leasing, as well as the timing of equipment replacement, also influence cash flow and debt levels, requiring integrated technical and financial-economic analysis (Park, 2011).

For these reasons, larger construction companies have increasingly incorporated asset-management tools and LCC analysis, following a path similar to that adopted in engineering economics and fleet-management practice (Fuller & Petersen, 1995; Park, 2011).

1.3 The Importance of Fleet Management for Road Construction Equipment

Fleet management in road-construction projects involves the planning, scheduling, operation, maintenance, and replacement of construction equipment while meeting the requirements of different project phases (Gransberg & Rueda, 2020). Poor management can lead to excessive machine downtime, frequent breakdowns, high fuel consumption, delays in meeting contractual deadlines, and, consequently, reduced profitability or reputational damage resulting from possible financial penalties (Gransberg, 2015; O'Connor, 2014).

Data-driven fleet-management practices, including usage monitoring, maintenance records, and detailed cost tracking, enable better equipment allocation, more effective scheduling of preventive maintenance, and more precise identification of the economically optimal replacement time (Gransberg, 2015; O'Connor, 2014).

In road projects, where production cycles are often intensive and equipment mobilization is expensive and time-consuming, these decisions are particularly important, justifying the development of specialized models for this context (Gransberg & Rueda, 2020; Gransberg, 2015).

1.4 EQUIPMENT MANAGEMENT IN A NATIONAL AND EUROPEAN CONTEXT

International literature on fleet management and LCC analysis has demonstrated the importance of integrating acquisition, operation, maintenance, and disposal costs into equipment-related decision-making (Gransberg, 2015; Fuller & Petersen, 1995). The life-cycle approach has gradually been incorporated into manuals and standards supporting infrastructure and physical-asset investment decisions, as exemplified by NIST Handbook 135 (Fuller & Petersen, 1995).

Nevertheless, in the construction sector, the systematic application of these principles to equipment management remains less widespread than in other fields, despite the availability of well-established models for heavy-equipment analysis (Gransberg, 2015; O'Connor, 2014). This gap creates opportunities for case studies in specific contexts, such as road-construction projects, where the application of LCC concepts can improve the efficiency of a construction company's fleet.

1.5 PROBLEM STATEMENT

Despite the recognized importance of equipment for construction-company competitiveness, investment and replacement decisions often rely on empirical criteria or short-term constraints rather than structured total life-cycle cost analysis (Gransberg, 2015; O'Connor, 2014). This approach can lead managers to retain obsolete or excessively costly equipment in service, or, alternatively, to make premature replacement decisions that fail to maximize the economic value of the assets (Gransberg, 2015).

In road-construction projects, demanding equipment-performance requirements and severe operating conditions reinforce the need to integrate maintenance, reliability, and availability costs into decision-making processes (Gransberg & Rueda, 2020; Gransberg, 2015). Nevertheless, the adoption of LCC models remains limited by data-collection and data-processing challenges, model complexity, and the lack of a long-term planning culture within organizations (Fuller & Petersen, 1995; Park, 2011).

Thus, the central problem addressed in this dissertation is the need to develop and apply a systematic methodology to support equipment-fleet replacement and planning decisions in a road-construction company, grounded in LCC analysis.

1.5.1 High ownership and operating costs of construction equipment

Costs associated with the ownership and operation of construction equipment include acquisition expenses, depreciation, financing, insurance, fuel, maintenance, repairs, and final disposal. LCC studies indicate that the operation and maintenance phase can represent more than half of an asset's total cost, often exceeding the initial investment (Fuller & Petersen, 1995; Gransberg, 2015).

When the management of these costs lacks reliable data and appropriate analytical models, identifying key cost drivers and optimizing them effectively becomes difficult (O'Connor, 2014; Gransberg, 2015). In road-construction companies, where fleets usually comprise dozens of equipment units distributed across several projects, the cumulative impact of suboptimal decisions on total ownership and operating costs can be substantial, justifying the use of more systematic LCC evaluation methods (Gransberg, 2015).

1.5.2 Current practices in equipment replacement and fleet planning

In practice, equipment-replacement decisions frequently rely on simplified criteria, such as chronological age, operating hours, or the occurrence of major breakdowns, without considering the evolution of marginal operation and maintenance costs (Gransberg, 2015; O'Connor, 2014). In some cases, fleet planning is conditioned by market opportunities or reactive responses to unexpected failures, rather than by a long-term strategy aligned with the company's project portfolio (Gransberg & Rueda, 2020).

There is also a lack of integrated decision-support tools that enable scenario simulation for replacement decisions, comparison of acquisition alternatives, and assessment of the economic impact of different fleet strategies (Gransberg, 2015; Fuller & Petersen, 1995).

This situation reveals an opportunity to develop LCC-based decision-support models tailored to the specific realities of road-construction companies.

1.5.3 Limitations in the systematic use of Life Cycle Costing (LCC) methods

The LCC concept is widely recognized as an appropriate approach for evaluating an asset's total cost from acquisition through end-of-life (Fuller & Petersen, 1995; Park, 2011). LCC models are applied across several sectors, including equipment fleets and infrastructure, to support investment and replacement decisions (Gransberg, 2015; O'Connor, 2014). However, their systematic implementation in construction companies faces practical obstacles, including the need for detailed historical data, the parameterization of uncertainty factors, and the integration of models into existing management processes (Fuller & Petersen, 1995; Park, 2011).

For construction equipment used in road projects, variability in operating conditions and diversity in machine types further complicate modelling efforts (Gransberg & Rueda, 2020; Gransberg, 2015). The adoption of equipment-level LCC methodologies therefore remains limited, particularly in the national business context, justifying detailed case-study research.

1.6 OBJECTIVES AND RESEARCH QUESTIONS

Given the identified problem, clear objectives are necessary to guide both the development of the research and the application of LCC models to the case study. These objectives are aligned with the operational reality of the analysed company and with the scientific frameworks of asset management, engineering economics, and equipment management (Fuller & Petersen, 1995; Gransberg, 2015; Park, 2011).

1.6.1 Main objective of the dissertation

The main objective of this dissertation is to develop and apply a decision-support methodology for the management of a road-construction equipment fleet, based on LCC analysis, using operational and financial data collected from a company operating in the Eastern European market.

To achieve this general objective, the following specific objectives were defined:

- To characterize the operational environment of the road-construction fleet, the data-collection tools and procedures implemented by the company's board of directors, and the potential

efficiency gains expected from the large volumes of information generated by the telemetry devices recently installed across the fleet.

- To review the state of the art on LCC models and their application to fleet and infrastructure management, with particular emphasis on recent developments in telematics data and their integration with business-intelligence (BI) tools for decision support.
- To develop or adapt an LCC model that supports replacement and planning decisions for critical equipment fleets by capturing acquisition, operating, maintenance, and disposal costs for key road-construction machines.
- To implement the model in an integrated and automated Excel workbook, with the possibility of connection to a cloud-based Power BI dashboard.
- To define and test decision criteria for repair, overhaul, and replacement based on economic life and cost thresholds, both for individual machines and for the fleet as a whole.
- To apply the model to the case study using historical data wherever possible, complemented by justified assumptions regarding cost, usage, and maintenance data required to evaluate different replacement scenarios.
- To analyse the results from an LCC-optimization perspective, identifying limitations and inefficiencies and proposing improvements through modern IT-based tools and opportunities in the management of large road-construction fleets.

1.6.2 Research questions and associated hypotheses

Based on the defined objectives, the following research questions were formulated:

Q1: What are the main cost components that determine the economically optimal replacement timing of the equipment under study, and how do these components evolve with equipment age and operating hours?

Q2: What are the main challenges faced by a manager when implementing an LCC approach at enterprise level?

Based on these research questions, the following hypotheses are advanced:

H1: Escalating maintenance costs, driven by the progressive need to replace worn components and by the associated downtime impacts on fleet availability, become predominant once a machine

reaches a certain age or operating-hour threshold. This cost escalation may justify replacement before technical end-of-life for at least a subset of the fleet, particularly where empirical decision-making leads managers to postpone economically justified replacement.

H2: The lack of systematized data represents a primary obstacle to the effective deployment and implementation of an LCC model within a company.

1.7 SCOPE AND DELIMITATIONS

This dissertation focuses on applying an LCC model to a selected fleet of construction equipment used in road projects, within the context of a multinational company. This choice enables an in-depth analysis but requires clearly defined limits regarding the types of projects, equipment classes, and time horizon considered

1.7.1 Types of road construction projects considered

The study focuses on heavy-equipment fleets involved in the construction of road projects of specific typologies, such as new road construction and pavement rehabilitation, as defined according to the company's reality and consistent with the literature's emphasis on earthmoving, compaction, and paving equipment (Peurifoy & Schexnayder, 2002; Gransberg & Rueda, 2020). Other project categories in which the company operates are not considered in detail, except where they share equipment or influence annual utilization.

1.7.2 Equipment classes under study

The study concentrates on equipment classes considered critical for road-project execution, such as hydraulic excavators, compaction rollers, and pavers. Among these classes, one primary category serves as the detailed case study, owing to its relevance in the company's project portfolio and its significant cost weight (Gransberg, 2015). Support equipment and small tools are not subject to detailed LCC analysis and appear only in aggregate form where relevant.

1.7.3 Economic, technical, and temporal delimitations

From an economic perspective, the LCC model considers direct equipment ownership and operating costs, including acquisition, financing, depreciation, maintenance, fuel, insurance, taxes, and disposal, consistent with the cost components described in LCC manuals (Fuller & Petersen, 1995; Park, 2011). Price-update rates and macroeconomic assumptions, such as inflation and interest rates, follow established engineering-economics literature (Park, 2011).

From a technical perspective, equipment is assumed to operate under normal usage conditions, with maintenance standards aligned with manufacturer recommendations and current construction-company practices (Gransberg & Rueda, 2020; Gransberg, 2015). In temporal terms, the study relies on a period with sufficiently complete cost and usage data, following the approach adopted in equipment life-cycle case studies (Gransberg, 2015; O'Connor, 2014).

2

EQUIPMENT MANAGEMENT AND LIFE-CYCLE COSTING: CONCEPTS AND LITERATURE REVIEW

2.1 EQUIPMENT MANAGEMENT IN CIVIL ENGINEERING

Equipment management in civil engineering ensures that appropriate machines remain available in optimal condition, at the required time and cost, to execute construction portfolios. This discipline encompasses the complete asset life cycle, from needs identification and equipment-type selection through acquisition, operation, maintenance, and eventual replacement or disposal (Gransberg, Popescu, & Ryan, 2006, pp. 19–24).

In road construction, coordinated earthmoving, compaction, and paving operations represent substantial project-budget expenditures. Effective equipment management therefore constitutes a primary mechanism through which contractors and public agencies control productivity, quality standards, and unit costs (Gransberg, Popescu, & Ryan, 2006, pp. 19–20; Edwards, 2003, pp. 20–21).

Conceptually, we can analyze equipment management at three interrelated levels:

- At the *strategic level*, organizations decide on long-term fleet policy, including the preferred balance between owned and hired machines, and target utilization rates across the fleet (Edwards, 2003, pp. 20–24; Gransberg, Popescu, and Ryan, 2006, pp. 19–24).
- At the *tactical level*, managers select equipment for particular projects and define the composition of fleets according to the specific work packages to be executed, taking into

account project conditions and machine performance requirements (Gransberg, Popescu, and Ryan, 2006, pp. 65–80, 121–139).

- At the *operational level*, supervisors allocate machines to specific tasks of the project, schedule their maintenance, and monitor performance and costs on a daily or weekly basis. Cost reporting and production reporting are seldom the joint responsibility of the equipment and production departments. (Gransberg, Popescu, and Ryan, 2006, pp. 163–195, 237–256).

Particularly at the strategic level, effective equipment management requires a quantitative framework based on engineering economics. Concepts such as the time value of money, capital recovery, and economic life link equipment cash-flow patterns to acquisition, retention, and replacement decisions (Blank & Tarquin, 2008, pp. 3–5, 80–98, 215–235). From this perspective, machines should not be regarded merely as project-specific cost centres, but as long-term assets whose economic performance depends on how they are used and maintained across multiple projects (Bull, 1993, pp. 1–10; O'Connor, 2014, pp. 1–4). Equipment management therefore seeks to balance technical performance, such as payload, power, and reliability, with economic performance, including fuel consumption, maintenance-cost escalation, downtime, and residual value (Blank & Tarquin, 2008, pp. 3–5, 80–98).

2.2 TYPES AND FUNCTIONS OF EQUIPMENT IN ROAD CONSTRUCTION PROJECTS

Road construction represents a complex production system requiring coordinated equipment types designed for specific tasks across multiple process stages. Standard classifications organize machines by function:

- *Earthmoving and loading:* bulldozers, scrapers, excavators, and wheel loaders perform cut-and-fill, trenching, and stockpile handling. Their excavation and loading rates and strongly influence unit earthwork costs.

  Bulldozers, or crawler tractors with blades, perform short-haul pushing, stripping, spreading, and rough grading, leveraging high tractive effort and low ground pressure for soft or uneven terrain typical of early earthworks.

  Scrapers combine cutting, self-loading, hauling, and dumping in a single unit, and are well suited to balanced cut-and-fill road sections where material can be moved economically over

medium haul distances without rehandling. More economical haul-loading at medium distances than wheel loaders.

Wheel loaders and excavators perform digging and loading functions: wheel loaders excel in stockpile loading and short-haul loading of trucks, while excavators and backhoes handle trenching, deep cuts, and foundation excavations, often in confined or irregular spaces. Backhoe loaders (or trenchers) produce consistent trench profiles and can be more efficient than excavators for long linear drains. (Gransberg, Popescu, and Ryan, 2006, pp. 67–70, 80–84, 84–86, 88–92, 94–100)

- *Hauling:* Haul units connect excavation and placement zones. Off-highway trucks deliver high-capacity transport on prepared haul roads, forming the backbone of large-scale road projects requiring long-distance material movement. Smaller trucks and articulated haulers serve shorter hauls or constrained sites, though detailed selection criteria remain project-specific. (Gransberg, Popescu, and Ryan, 2006, pp. 92–94).
- *Grading and shaping:* Motor graders provide precise control of grade, crossfall, and surface smoothness essential for road formation, sub-base, and base course layers. Adjustable blade angle, tilt, and articulation capabilities enable accurate layer thickness and alignment control following rough shaping by dozers or scrapers. While dozers support intermediate shaping tasks, graders serve as primary surface-forming equipment to achieve the tight tolerances required for pavement quality (Gransberg, Popescu, and Ryan, 2006, pp. 70–76, 86–88).
- Paving: Asphalt pavers and concrete slip-form pavers place final surfacing materials, typically operating within coordinated equipment trains that include feeders, transfer vehicles, and finishing units. Paver capacity and operational reliability remain critical, as paving operations exhibit extreme sensitivity to equipment interruptions or delays (Gransberg, 2006).
- Compaction: single-drum and tandem-drum rollers, vibratory compactors and pneumatic tyred rollers. Their function is to densify embankment, subgrade, and pavement materials to specified densities and stiffnesses. Soil compactors exert loads through static and dynamic (vibratory) forces, with drum width and amplitude influencing coverage and depth of effect; asphalt rollers combine compaction and surface finishing for bituminous layers. (Gransberg, Popescu, and Ryan, 2006, pp. 65–67). Matching compaction capacity to paver output is key to avoiding cold joints and under-compaction (Edwards, 1997; Gransberg, 2006).

- Structural and ancillary works employ cranes, forklifts, and concrete placing equipment to support drainage systems and pavement construction. Lifting equipment—including mobile cranes, crawler cranes, and forklifts—facilitates bridge construction, culvert installation, retaining walls, gantries, and heavy precast component placement along the road alignment (Gransberg, Popescu, and Ryan, 2006, pp. 65–76, 80–100, 100–118, 202–208)
- Crane selection for large scale structural elements like overpass beams depend on load charts, rigging configurations, and site access conditions, which collectively determine feasible crane types to be deployed. (Gransberg, Popescu, and Ryan, 2006, pp. 100–111, 197–201).
- Support and service equipment: include water trucks, fuel and lubrication trucks, sweepers and also small asphalt plants. This auxiliary equipment sustains primary operations while maintaining safe, continuous working conditions. Specialized equipment such as power generators, compressors, pumps, and articulated extending booms supports pavement and deck construction, complemented by diverse machine attachments that adapt primary equipment to specific project requirements (Gransberg, Popescu, and Ryan, 2006, pp. 94–100, 202–208).

2.3 STRATEGIES OF OWNERSHIP VERSUS RENTAL

Equipment-acquisition strategy determines whether an organization relies primarily on ownership or rental arrangements. Ownership requires a significant initial investment and continuing costs, including financing, insurance, depreciation, and storage, but can yield lower long-term hourly costs when equipment is highly utilized across multiple projects. Rental converts capital-intensive expenditure into periodic hire charges and transfers risks such as residual-value uncertainty, underutilization, and technological obsolescence to the equipment supplier (Blank & Tarquin, 2008, pp. 8–13; Gransberg, Popescu, & Ryan, 2006, pp. 20–24, 225–236; Edwards, 2003, pp. 23–24).

Ownership is generally more economical when utilization is predictable and sufficiently intensive, when the equipment serves recurring needs across the project portfolio, and when capital availability is not a major constraint. Under these conditions, capital recovery, interest, and fixed ownership charges can be spread over a large number of productive hours, reducing unit costs relative to rental. Ownership also provides greater control over maintenance standards, equipment customization, and operator training (Blank & Tarquin, 2008, pp. 8–13; Gransberg, Popescu, & Ryan, 2006, pp. 20–24, 225–236; Edwards, 2003, pp. 20–27).

Rental is more appropriate for intermittent, project-specific, or uncertain requirements, such as specialized machinery used infrequently or temporary capacity increases. It avoids capital commitment, aligns costs more closely with project cash flows, and provides access to newer technologies without long-term exposure to obsolescence (Gransberg, Popescu, & Ryan, 2006, pp. 225–236; Blank & Tarquin, 2008, pp. 8–13; Edwards, 2003, pp. 23–25).

From an economic perspective, the two strategies generate different cash-flow patterns. Ownership involves an initial purchase cost, annual ownership and operating expenses, and eventual salvage recovery, whereas rental involves periodic hire charges, sometimes supplemented by mobilization fees or minimum-usage payments. Present-worth or equivalent-annual-cost analysis can identify the utilization level, analysis horizon, or rate structure at which the alternatives become economically equivalent (Blank & Tarquin, 2008, pp. 8–13, 80–98, 107–118; Gransberg, Popescu, & Ryan, 2006, pp. 225–236).

2.4 PLANNING, SIZING, AND UTILIZATION OF FLEETS

Fleet planning, sizing, and utilization determine the number of equipment units required, their operational assignments, and their expected usage intensity. Production planning provides the basis for these decisions by quantifying earthworks, pavement, and auxiliary-work volumes, together with the time available for their execution (Gransberg, Popescu, & Ryan, 2006, pp. 121–139).

Equipment selection for specific operations, such as excavation, hauling, grading, and compaction, relies on capacity and cycle-time analysis to estimate production rates. These estimates guide the assembly of equipment groups capable of achieving the required output while avoiding bottlenecks and excessive idle time. In an earthwork operation involving cutting, hauling, placing, and compacting, system output is constrained by the slowest or least-capable stage; an unbalanced allocation of machines increases idle time and operating costs without increasing production (Gransberg, Popescu, & Ryan, 2006, pp. 121–139).

Fleet utilization is commonly defined as the ratio of productive operating hours to the hours during which equipment is available. Higher utilization spreads ownership costs over more productive hours, reducing hourly cost, but may also accelerate wear and increase maintenance requirements. Conversely, low utilization indicates that ownership costs are spread over fewer productive hours, suggesting that fleet size, project scheduling, or the balance between owned and rented equipment should be reconsidered (Gransberg, Popescu, & Ryan, 2006, pp. 19–24, 39–64).

2.5 FLEET MANAGEMENT IN ROAD CONSTRUCTION PROJECTS

Fleet management in road-construction projects coordinates the deployment and control of equipment across multiple work fronts. Its objective is to ensure that machines are available where and when they are required, while maintaining acceptable levels of cost, productivity, and work quality (Gransberg, Popescu, & Ryan, 2006, pp. 19–64, 163–195, 237–256).

2.5.1 Selection of equipment and construction methods

Equipment selection for road projects is closely linked to construction-method selection. Each construction method requires specific decisions regarding task sequence, equipment selection and deployment, and material flows (Gransberg, Popescu, & Ryan, 2006, pp. 65–80, 121–139).

Each construction method implies different fleet configurations, with distinct combinations of machines, cost structures, and risk profiles. The machine-selection process must consider factors such as soil type, rock hardness, groundwater conditions, haul distances, topography, climate, environmental constraints, site access, and the space available for equipment manoeuvring. Similarly, method and equipment choices for compaction depend on layer thickness, width, and material stiffness, as different rollers achieve different compaction depths and surface finishes (Gransberg, Popescu, & Ryan, 2006, pp. 65–80, 80–94, 202–208).

Gransberg, Popescu, and Ryan emphasize the need to select machines adequately for each work front. For example, scrapers are most effective in materials that can be cut and loaded efficiently and where haul distances are neither too short nor too long. In contrast, an excavator-and-truck combination is more flexible in confined spaces and variable materials, although it may have higher unit costs if the machines are not well matched (Gransberg, Popescu, & Ryan, 2006, pp. 88–94).

Manufacturer datasheets and standard reference values provide key technical characteristics for each equipment type, including engine power, bucket, blade, or drum capacity, operating weight, payload, travel speed, and typical operating envelope. These characteristics support the estimation of machine productivity and the identification of equipment combinations capable of meeting the intensity and duration of the planned operations (Gransberg, Popescu, & Ryan, 2006, pp. 67–76, 80–94; Edwards, 2003, pp. 53–82).

A systematic method for estimating machine productivity is therefore an essential component of fleet selection. For example, in a load-and-haul operation, the objective is to identify a loader-and-truck combination that achieves the required production rate at the lowest practicable unit cost of material movement. After a shortlist of technically feasible and cost-effective configurations has been established, the final selection should consider the company's financial and logistical resources, as well as other project-specific constraints.

2.5.2 Resource allocation and production planning

Resource allocation and production planning involve optimizing the distribution of equipment across tasks, crews, and project locations to meet project objectives. Once methods and fleets have been selected, managers determine machine quantities for each work front, establish spatial sequencing, such as working from multiple headings, and coordinate operations so that downstream activities avoid resource shortages or delays caused by preceding operations. At the project level, these decisions integrate with network scheduling and critical-path analysis, where equipment availability and crew productivity directly influence activity durations and overall completion time (Gransberg, Popescu, & Ryan, 2006, pp. 163–195).

Cycle-time analysis is central to production planning for equipment-intensive operations. For example, the truck cycle time in a cut-and-fill operation comprises loading, loaded travel, dumping, and empty return, with each component influenced by haul distance, travel speed, and operating conditions. By estimating these times and combining them with machine capacities, such as bucket size and truck payload, managers can calculate production rates and determine whether resource allocation meets the required output or needs adjustment (Gransberg, Popescu, & Ryan, 2006, pp. 121–139).

Balancing resources so that production flows without prolonged waiting at any stage is the main objective. If too few trucks are assigned relative to loader capacity, the loader experiences idle time; if too many trucks are assigned, trucks queue at the loading point. The loading capacity must therefore be matched to the hauling capacity of the truck fleet, avoiding both idle loading equipment and excessive truck queuing (Gransberg, Popescu, & Ryan, 2006, pp. 121–139).

In terms of cost, resource allocation affects both variable operating expenditures and the effective use of ownership costs. Misallocation can result in periods in which machines are on site but underused, meaning that ownership costs are incurred without corresponding productive output.

Conversely, overloading certain units can increase breakdowns and maintenance costs (Gransberg, Popescu, & Ryan, 2006, pp. 39–64, 163–195).

2.5.3 Maintenance, reliability, and operational availability

Maintenance policies shape equipment reliability and availability, which in turn affect project productivity and costs. Maintenance activities are commonly classified as preventive, comprising routine servicing, inspections, and scheduled component replacements; predictive, comprising condition-based interventions supported by diagnostic data; and corrective, comprising actions taken after failure. Reliability is the probability that equipment performs without failure for a specified period under defined conditions, while operational availability is the proportion of time during which equipment is ready to perform its intended function when required (Gransberg, Popescu, & Ryan, 2006, pp. 39–64, 237–256).

Effective preventive maintenance can reduce the frequency and severity of failures, thereby increase reliability and reduce unplanned downtime. However, an extensive preventive-maintenance programme also increases labour and parts costs. Fleet managers must therefore balance planned and unplanned maintenance expenditure, together with the associated downtime, over the equipment's life (Gransberg, Popescu, & Ryan, 2006, pp. 237–256; Edwards, 2003, pp. 150–166). Manufacturer-defined preventive-maintenance plans are frequently adopted for this purpose, as they provide structured service intervals and component-replacement guidance.

As machines age, even with good maintenance, wear and fatigue lead to more frequent failures and more extensive repairs, increasing operating costs and reducing availability. This pattern directly informs economic-life analysis and becomes decisive in replacement decisions (Gransberg, Popescu, & Ryan, 2006, pp. 39–64; O'Connor, 2014, pp. 1–4).

The operational availability of each machine affects both project scheduling and cost. Low availability may require managers to retain additional units or rent supplementary capacity, increasing ownership or rental costs. It may also cause project delays, which may result in contractual penalties (Gransberg, Popescu, & Ryan, 2006, pp. 39–64, 237–256).

High machine availability enables leaner fleets and more reliable production planning, but may require a more demanding maintenance programme and higher initial investment in higher-quality equipment (Edwards, 2003, pp. 150–166). Maintenance-management systems, including work-order records, service histories, and cost tracking, are therefore essential to support strategic

decisions, such as whether a persistently unreliable machine should be overhauled or replaced (Gransberg, Popescu, & Ryan, 2006, pp. 237–256).

2.5.4 Telemetry systems and fleet management software with real-time data input

By improving the accuracy and timeliness of data inputs, telemetry can enhance LCC models that would otherwise depend on static historical averages. Real-time information on utilization, fuel consumption, engine load, location, and maintenance events supports more reliable cost attribution, preventive-maintenance scheduling, identification of high-cost units, and replacement analysis (O'Connor, 2014, pp. 1–4; Gransberg, Popescu, & Ryan, 2006, pp. 293–304).

Standardized data-entry procedures ensure that operating and maintenance records remain accurate and current. This enables reliable data extraction to support decisions such as preventive-maintenance scheduling and the identification of high-cost units. Real-time data from onboard meters and GPS systems can automatically capture operator information, working hours, engine load, speed, fuel consumption, and location, which can be compiled into dashboards displaying key performance indicators such as utilization rate, idle time, and maintenance compliance (Gransberg, Popescu, & Ryan, 2006, pp. 293–304).

2.6 OWNERSHIP AND OPERATING COSTS OF EQUIPMENT

This section examines how total equipment costs are structured into ownership costs, also referred to as standing costs, and operating costs, also referred to as running costs, and how each category evolves over time. Ownership costs are incurred because the organization possesses the equipment, irrespective of whether it is operating or idle, whereas operating costs arise only when the machine is used (Gransberg, Popescu, & Ryan, 2006, pp. 19–29). This distinction is fundamental to life-cycle cost analysis and replacement decisions, because utilization and age affect the two cost groups differently (O'Connor, 2014, pp. 1–4).

2.6.1 Components of ownership costs

Ownership costs comprise the initial capital outlay and its recovery over time, together with financing, risk-protection, and storage costs. The initial investment includes the purchase price and related expenses, such as delivery, initial assembly, and purchase taxes, which must be recovered through productive use over the equipment's economic life (Blank & Tarquin, 2008, pp. 80–98). In

LCC analysis, capital-recovery techniques convert the net capital invested, net of expected salvage value, into an equivalent annual amount reflecting both the return of capital and the return on capital (Blank & Tarquin, 2008, pp. 80–98, 107–118; Gransberg, Popescu, & Ryan, 2006, pp. 20–24).

Depreciation represents the systematic allocation of capital cost over time, reducing book value and reflecting the consumption of the asset's economic potential (Blank & Tarquin, 2008, pp. 287–310). Interest is the cost of tying up capital in the equipment, either because funds could have earned a return elsewhere or because loans need to be serviced. It is often calculated on the average undepreciated value of the asset over the service period (Blank & Tarquin, 2008, pp. 5–8; Edwards, 2003, pp. 60–87).

Insurance, mandatory inspections, and taxes, where applicable, provide financial protection against certain risks, such as physical damage and liability, and ensure compliance with legal obligations. Storage costs arise from the need to house and protect the asset when it is not in use (Gransberg, Popescu, & Ryan, 2006, pp. 20–24; Edwards, 2003, pp. 60–87).

From a managerial perspective, ownership costs are often treated as fixed within a given year, as they are essentially the same regardless of whether the machine is heavily used. This creates an incentive either to maintain high utilization for owned equipment or to adjust fleet size and acquisition strategy when utilization remains consistently low (Edwards, 2003, pp. 60–87; Gransberg, Popescu, & Ryan, 2006, pp. 20–24).

2.6.1.1 Initial investment and capital recovery

The capital-recovery factor converts the net capital invested in an asset—purchase price less the present worth of its salvage value—into an equivalent annual cost comprising both a return of capital and a return on capital (Blank & Tarquin, 2008, pp. 80–98, 107–118). Expressing capital consumption as an annual cost allows more meaningful comparisons among machines with different purchase prices, service lives, and salvage-value prospects (Blank & Tarquin, 2008, pp. 107–118; Gransberg, Popescu, & Ryan, 2006, pp. 20–24).

2.6.1.2 Depreciation methods and book value

Depreciation methods, such as straight-line, sum-of-the-years-digits, and double-declining-balance, define how capital cost is allocated over time and how asset book value decreases. Straight-line

depreciation assigns equal charges to each period, whereas accelerated methods allocate more cost to earlier years, which may better reflect the pattern of economic usefulness or maintenance requirements and may offer tax advantages where permitted (Blank & Tarquin, 2008, pp. 287–310).

In equipment management, book value is relevant for accounting, tax calculations, and, in some cases, internal rental rates or replacement thresholds. However, the current salvage or disposal value may differ from book value because of market conditions, a difference that must be recognized in LCC models (Gransberg, Popescu, & Ryan, 2006, pp. 20–24).

The depreciation can be calculated using 3 methods:

Straight-Line Depreciation (SL method)

This is the most commonly used method and the simplest. Consists in assuming that depreciation has the same amount every year until the asset book value reaches its salvage value. This depreciation model assumes the assets productivity remains fairly stable along the useful life of the machine.

Sum of the Years Digits Depreciation (SYD method)

This depreciation method inflicts a higher loss of value on the first years of life than Stright Line method. It's more common with machine that have higher wear rate on early years. Equipment like pavers, loaders, graders or excavators can fit this kind of scenario.

Double-Declining Balance Depreciation (DDB method)

This depreciation model inflicts even higher value loss than SYD method and should be used only for equipment that has very short expected economic life. Hauling equipment operating in intensive continuous shifts. (Gransberg, Popescu, and Ryan, 2006, pp. 20–24)

Table 1: Depreciation methods

Method	**Annual Depreciation D_k**	**Book Value BV_k**
SL	$D_k = \frac{IC - S}{N}$	$BV_k = IC - k \cdot \frac{IC - S}{N}$

Method	Annual Depreciation D_k	Book Value BV_k
SYD	$D_k = \frac{N-k+1}{\frac{N(N+1)}{2}} \cdot (IC - S)$	$BV_k = IC - \sum_{i=1}^{k} D_i$
DDB	$D_k = \frac{2}{N} \cdot BV_{k-1}$	$BV_k = BV_{k-1} \cdot \left(1 - \frac{2}{N}\right) BV_0$

Meaning:

S is the salvage value (end-of-life value)

N is the useful life in years

k Is the current year (1 to N)

BV_k is the book value at end of year k

BV_{k-1} is the book value at start of year k

$BV_0 = IC$ is the initial capital invested (purchase cost)

D_k is the depreciation expense in year k

Example comparing the 3 methods:

For a machine costing new 100000€, Salvage value of 10000€ and an expected life of 5 years.

Table 2: Comparison between 3 depreciation methods

Year k	**SL** D_k	**SL** BV_k	**SYD** D_k	**SYD** BV_k	**DDB** D_k	**DDB** BV_k
0	-	100,000	-	100,000	-	100,000
1	18,000	82,000	30,000	70,000	40,000	60,000
2	18,000	64,000	24,000	46,000	24,000	36,000
3	18,000	46,000	18,000	28,000	14,400	21,600
4	18,000	28,000	12,000	16,000	8,640	12,960
5	18,000	**10,000**	6,000	**10,000**	*2,960**	**10,000***

* The DDB fifth-year amount is adjusted from the unadjusted €5,184 to €2,960, because only €2,960 remains between the opening book value of €12,960and the €10,000 salvage value.

2.6.1.3 Interest, insurance, taxes, and storage

Interest is conceptually the cost of using money, either as a borrowing cost or as the opportunity cost of funds diverted from other uses. For equipment, it is typically estimated on the average balance of undepreciated capital over a given period (Blank & Tarquin, 2008, pp. 5–8; Edwards, 2003, pp. 60–87). Insurance protects against risks such as damage, theft, or liability arising from equipment use, and insurance premiums form part of the standing cost of ownership (Edwards, 2003, pp. 60–87).

Taxes may include property or asset taxes levied on equipment value, depending on the jurisdiction. Storage costs cover the facilities and services required to house plant when it is not in use, including sheds, yards, and security arrangements (Gransberg, Popescu, & Ryan, 2006, pp. 20–24; Edwards, 2003, pp. 60–87). Taxes can have a substantial impact on ownership costs, particularly in fiscal environments where investment in equipment and its financing costs cannot be partially or fully deducted from the amount subject to taxation.

2.6.2 Components of operating costs

Operating costs reflect the resources consumed directly through equipment use and typically increase with operating hours and equipment age. Fuel and lubricants provide the energy and lubrication required for operation; maintenance and repairs restore performance and reliability; tyres and other wear parts gradually degrade and require replacement; consumables, such as filters and oils, are used up during operation; and operating labour provides the human input required to run the machines (Gransberg, Popescu, & Ryan, 2006, pp. 25–30; Edwards, 2003, pp. 25–29).

These costs form the running cost per unit of time or per unit of output and are central to economic-life calculations. In particular, maintenance and repair costs tend to rise as equipment ages, making them a decisive element in replacement analysis (Gransberg, Popescu, & Ryan, 2006, pp. 39–64; O'Connor, 2014, pp. 1–4).

2.6.2.1 Fuel and lubricants

Fuel cost is typically calculated as fuel consumption per hour, or per unit of work, multiplied by the fuel price. Both factors can vary over time and across projects. Fuel consumption depends on engine size, load factor, operating conditions, and operator behaviour; heavy, stop-start operations or work on steep gradients can increase consumption (Gransberg, Popescu, & Ryan, 2006, pp. 25–29).

Fuel price is an external variable subject to market volatility. O'Connor highlights that changes in fuel price can materially alter life-cycle cost estimates and replacement timing, especially for fuel-intensive equipment such as haul trucks (O'Connor, 2014, pp. 1–4). Lubricants and other fluids are consumed during routine servicing and operation. Although their cost is lower than that of fuel, they are essential for maintaining reliability and reducing wear (Gransberg, Popescu, & Ryan, 2006, pp. 25–29).

2.6.2.2 Maintenance and repairs

Maintenance and repairs are central to the economic behaviour of equipment over time. Preventive maintenance includes scheduled tasks such as oil changes, filter replacements, inspections, and adjustments, which are designed to control wear and detect problems before failure occurs (Gransberg, Popescu, & Ryan, 2006, pp. 39–64, 237–256). Corrective repairs include both minor interventions, such as replacing hoses, seals, or minor components, and major overhauls, such as engine rebuilds or transmission replacements. These interventions tend to become more frequent as machines age (Edwards, 2003, pp. 25–27; Gransberg, Popescu, & Ryan, 2006, pp. 39–64).

From an LCC perspective, maintenance and repair costs are often represented as a function that increases with equipment age or cumulative operating hours, reflecting the wear-out phase of the asset (Gransberg, Popescu, & Ryan, 2006, pp. 39–64; O'Connor, 2014, pp. 1–4). In the early years, maintenance expenditure is generally lower and dominated by routine tasks. As components reach the end of their service life, more expensive repairs and overhauls become necessary, and the risk of major failures increases (Gransberg, Popescu, & Ryan, 2006, pp. 39–64). This rising pattern of operating cost eventually offsets the declining ownership cost associated with longer retention periods, forming the upward arm of the economic-life curve (Blank & Tarquin, 2008, pp. 215–235; O'Connor, 2014, pp. 1–4)

2.6.2.3 Tyres, wear parts, and consumables

Tyres and wear parts constitute a distinct subset of operating costs because they can represent significant expenditure for certain equipment types and are closely linked to working conditions. Tyres on dump trucks, scrapers, and graders wear as a result of abrasion, cuts, and impact. Their service life depends on haul-road conditions, load, inflation pressure, and maintenance practices (Gransberg, Popescu, & Ryan, 2006, pp. 25–29; O'Connor, 2014, pp. 7–8).

Ground-engaging tools, including bucket teeth, cutting edges on dozer blades and graders, and ripper shanks, wear down through interaction with soil and rock. Their timely replacement is essential to maintain productivity and avoid increased fuel consumption (Gransberg, Popescu, & Ryan, 2006, pp. 25–29).

Consumables, such as filters, coolant, brake fluid, and grease, are used during routine maintenance and operation. Although the cost of each individual item may be low, their cumulative effect over thousands of operating hours is non-negligible and must be included in operating-cost estimates (Gransberg, Popescu, & Ryan, 2006, pp. 25–29).

Accurate tracking of tyre and wear-part life, together with operating conditions, can support more refined LCC models and maintenance planning. In practice, however, tyre or track replacement intervals are often defined according to manufacturer-recommended intervals, such as those published in manufacturer's own handbooks, like for example in *Caterpillar's Performance Handbook*.

2.6.2.4 Operating labor and associated charges

Operating labour encompasses the wages, benefits, and associated costs of equipment operators and, in some cases, support personnel such as signalers, spotters, and mechanics whose work is directly linked to equipment operation (Gransberg, Popescu, & Ryan, 2006, pp. 29–30). Although labour is often separated from equipment costs in accounting systems, the combined cost of the machine and its operator per unit of output is the relevant quantity for cost estimation and optimization (Edwards, 2003, pp. 25–29).

Labour-related charges may include overtime premiums, travel time to and from site, shift allowances, and operator-training costs. These charges can influence decisions concerning shift patterns, automation, and the choice between more or less labour-intensive construction methods (Edwards, 2003, pp. 25–29).

2.6.3 Service life of equipment and replacement

Service life is not a single concept. It comprises physical life, which refers to how long a machine can operate; economic life, which refers to how long it should operate from a cost perspective; and technological life, which refers to how long it remains competitive with newer alternatives (Gransberg, Popescu, & Ryan, 2006, pp. 39–46). Replacement decisions should consider all three

dimensions, although economic considerations are usually paramount in fleet management (Blank & Tarquin, 2008, pp. 215–235; O'Connor, 2014, pp. 1–4).

2.6.3.1 Physical, economic, and technological life

Physical life is the period until a machine can no longer perform its function safely or reliably, even with increasing maintenance and repair. At the end of its physical life, failures become unacceptable in frequency or severity, and a major rebuild or replacement is necessary if the intended function is to continue (Gransberg, Popescu, & Ryan, 2006, pp. 40–41).

Economic life is defined as the age at which the equivalent annual cost of owning and operating the equipment is minimized. Beyond this age, retaining the machine for a longer period increases its average annual cost (Blank & Tarquin, 2008, pp. 215–235; Gransberg, Popescu, & Ryan, 2006, pp. 46–58). Economic life is therefore the retention period during which owning and operating the machine achieves the lowest overall cost relative to replacement.

Technological life refers to the period during which a machine remains productive, sufficiently accurate, and compliant with environmental and safety requirements, despite using older technology. For example, stricter emissions regulations or the introduction of telematics and driver-assistance systems can shorten the effective life of older machines by making them less acceptable or more costly to operate than newer alternatives, even before they reach the end of their physical life (Gransberg, Popescu, & Ryan, 2006, pp. 41–46).

In practice, these life concepts may differ considerably. For example, a haul truck may have a physical life of 15 to 20 years if major components are overhauled, but its economic life may be shorter if maintenance and fuel costs increase to the point where a new, more efficient truck would result in lower annual costs (Gransberg, Popescu, & Ryan, 2006, pp. 39–46; O'Connor, 2014, pp. 1–4).

2.6.3.2 Classical criteria for determining economic life

Classical economic-life analysis uses equivalent-annual-cost or present-worth methods to determine the age at which equipment should ideally be replaced. For each possible replacement age, the total discounted cost of acquiring, owning, operating, and eventually selling the equipment is calculated and converted into an equivalent annual cost. Economic life corresponds to the age at which this annual cost is minimized (Blank & Tarquin, 2008, pp. 215–235; Gransberg, Popescu, & Ryan, 2006, pp. 46–58).

Ownership cost per year tends to decline over time because the remaining capital to be recovered becomes smaller. In contrast, operating cost per year tends to increase because of rising maintenance, repair, and downtime costs. The combination of these opposing trends produces a U-shaped total annual-cost curve, whose minimum corresponds to the economic life (Blank & Tarquin, 2008, pp. 215–235; O'Connor, 2014, pp. 1–4).

An equivalent way to express this criterion is to compare the marginal cost of keeping the equipment for one additional year with the average annual cost up to that year. If the marginal cost of the next year is less than or equal to the average cost, retention remains economical. Once the marginal cost exceeds the average cost, replacement becomes economically justified (Blank & Tarquin, 2008, pp. 215–235). Implementing this analysis requires estimates of expected annual operating costs, salvage values for each prospective age, and an appropriate discount rate. O'Connor identifies uncertainty in these inputs as a major practical challenge (O'Connor, 2014, pp. 1–4).

2.6.3.3 Residual value, second-hand market, and obsolescence

Residual or salvage value is the expected market value of equipment at the end of its service life or at a chosen analysis horizon. It appears as a positive cash flow in economic-life calculations and reduces the net cost of ownership (Blank & Tarquin, 2008, pp. 215–235). Salvage value depends on physical condition, age, brand, model, and prevailing conditions in the second-hand market. It may also be influenced by technological and regulatory changes that affect demand for used equipment (Gransberg, Popescu, & Ryan, 2006, pp. 41–46).

If residual values decline faster than expected because of obsolescence or market saturation, the cost of retaining equipment for longer increases, potentially shortening its economic life (Blank & Tarquin, 2008, pp. 215–235; O'Connor, 2014, pp. 1–4).

Obsolescence may be technological, regulatory, or economic. Technological obsolescence occurs when new machines offer significantly better performance, lower operating costs, or improved safety. Regulatory obsolescence occurs when new regulations, such as emission standards, make older equipment costly or impractical to operate. Economic obsolescence arises when changes in demand reduce the market value of particular types of equipment (Gransberg, Popescu, & Ryan, 2006, pp. 41–46).

2.7 CONCEPT OF LIFE-CYCLE COST (LCC)

In construction, life-cycle costing is defined as a method for systematically considering all costs associated with the acquisition, operation, maintenance, replacement, and disposal of an asset over a specified period, using discounting to express them on a comparable basis. LCC enables comparisons that account for the timing and magnitude of capital, operating, maintenance, replacement, and disposal costs, rather than focusing solely on the initial purchase price (Bull, 1993, pp. 1–10; Blank & Tarquin, 2008, pp. 80–98).

In fleet management, LCC is commonly used to evaluate equipment selection, ownership-versus-rental scenarios, maintenance strategies, and replacement-timing decisions (Gransberg, Popescu, & Ryan, 2006, pp. 19–29; O'Connor, 2014, pp. 1–4).

The general LCC framework involves defining the objective of the analysis, such as minimizing cost for a given performance level; specifying the analysis period and discount rate; identifying the relevant cost elements; estimating their timing and magnitude; and applying present-worth or equivalent-annual-cost calculations to compare alternatives (Bull, 1993, pp. 1–14; Blank & Tarquin, 2008, pp. 80–98, 107–118).

For equipment, LCC models classify costs into ownership costs, including capital recovery, interest, insurance, storage, and taxes, and operating costs, including fuel, maintenance, repairs, consumables, and labour. These costs are estimated for each year or analysis period (Gransberg, Popescu, & Ryan, 2006, pp. 19–29; O'Connor, 2014, pp. 1–4). Salvage value at the end of the period is included as a negative cost, or benefit. The discount rate influences the relative weight given to near-term and long-term costs: higher discount rates place greater emphasis on early costs and less emphasis on distant operating and maintenance costs (Blank & Tarquin, 2008, pp. 80–98).

2.7.1 Applications of LCC in infrastructures and equipment

LCC has been applied in building design, highway alignment and pavement-type selection, bridge-maintenance strategies, and other infrastructure decisions in which costs occur over long periods and design choices influence future operating expenditure (Bull, 1993, pp. 1–22). For example, a road authority might compare asphalt and concrete pavements by estimating construction, maintenance, and rehabilitation costs over a 30- or 40-year horizon and selecting the option with the lowest present cost, subject to performance and risk considerations (Bull, 1993, pp. 1–22).

The same concept can be extended to the fleets of heavy machines used to construct such infrastructure, although some adaptations are required. In equipment management, LCC is used to compare alternative machines, such as different models of haul trucks, by estimating their ownership and operating costs over their expected lives and expressing them as equivalent annual costs or costs per unit of output (Gransberg, Popescu, & Ryan, 2006, pp. 19–38; O'Connor, 2014, pp. 1–4). It also supports replacement analysis by providing the cost streams required to determine economic life or to compare retention and replacement options under different assumptions regarding future operating costs (Blank & Tarquin, 2008, pp. 215–235; O'Connor, 2014, pp. 1–4).

2.7.2 Advantages and limitations in fleet management

The main advantage of using LCC in fleet management is that it aligns decisions with long-term cost minimization rather than with short-term budget constraints or initial purchase price alone. By making all relevant costs visible and time-weighted, LCC can reveal that equipment with a higher purchase price but lower fuel and maintenance costs may have a lower total cost than a cheaper but less efficient alternative. It can also show that timely replacement may reduce total cost despite the associated capital outlay (Bull, 1993, pp. 1–10; Gransberg, Popescu, & Ryan, 2006, pp. 46–64). LCC further provides a common metric for comparing ownership and rental strategies, as well as different maintenance regimes, on a consistent economic basis (Blank & Tarquin, 2008, pp. 80–98; O'Connor, 2014, pp. 1–4).

However, LCC has limitations arising from data quality, model assumptions, and uncertainty. Forecasts of operating and maintenance costs, future utilization, and discount rates are often based on historical data, generic manufacturer information, or empirical assumptions (Bull, 1993, pp. 10–14; O'Connor, 2014, pp. 1–4). In addition, fleet managers frequently treat uncertain parameters deterministically, ignoring variability and risk. Some key inputs should instead be treated as random variables and analysed using stochastic methods, which, although more complex, can provide more realistic decision support (O'Connor, 2014, pp. 1–4).

Finally, LCC focuses on cost and does not directly incorporate qualitative factors such as safety, ease of operation, or organizational capacity. These factors must therefore be considered separately, and further evaluation may be required before a final decision is made (Bull, 1993, pp. 10–14).

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2.8 PRINCIPLES OF ECONOMICS AND PROJECT APPRAISAL

Individual equipment decisions, as well as fleet-management decisions, should be considered within the framework of engineering economics and project appraisal. Principles such as the time value of money, discount rates, present value, and internal rate of return are required to establish a well-reasoned investment appraisal for a new machine or to justify a costly repair to an older one.

2.8.1 Time value of money and discount factors

The time value of money, expressed through interest and discount factors, allows costs and benefits occurring at different times to be compared meaningfully. Project-appraisal methods, including present-worth analysis, equivalent-annual-cost analysis, internal rate of return, payback period, and cost-benefit analysis, provide tools for assessing whether investments and strategies are economically justified. The concept assumes that a unit of currency today is worth more than the same unit in the future because it can earn a return if invested. Interest rates quantify this return, while discount factors, derived from interest rates, translate future amounts into present equivalents, or vice versa (Blank & Tarquin, 2008, pp. 3–8, 80–98, 107–118, 124–151, 160–180; Bull, 1993, pp. 3–10).

For example, a future cost incurred during the operation or maintenance phase of equipment ownership must be discounted to its present value before being combined with initial investment costs in an LCC analysis (Blank & Tarquin, 2008, pp. 80–98; Bull, 1993, pp. 6–9).

In fleet management, discounting is particularly important because many significant costs occur in the future, including major component replacements, overhauls, and eventual salvage recovery. A higher discount rate reduces the present importance of future costs relative to initial expenditure, potentially favouring alternatives with lower first costs but higher long-term operating costs. Conversely, a lower discount rate increases the weight of future savings associated with more efficient equipment or delayed replacement (Blank & Tarquin, 2008, pp. 80–98). As a reference, European Commission guidance for large infrastructure projects co-financed by the EU refers to discount rates of 3% or 5%, depending on the member-state category, Cohesion or Standard.

2.8.2 Present value methods and equivalent annual cost

Present-value, or present-worth, methods sum the discounted values of all cash flows associated with an alternative to obtain a single present value, which can then be compared across alternatives (Blank & Tarquin, 2008, pp. 80–98). Equivalent uniform annual cost converts this present value into an equal annual amount over the analysis period, providing a measure of average annual cost that is particularly useful for comparing alternatives with different lives (Blank & Tarquin, 2008, pp. 107–118).

In equipment management, EUAC is often used to compare different machine models, assess ownership-versus-rental alternatives, and determine economic life by identifying the age at which EUAC is minimized (Gransberg, Popescu, & Ryan, 2006, pp. 46–58; O'Connor, 2014, pp. 14–22).

For example, in replacement analysis, the total discounted cost of owning and operating equipment up to a given age, including salvage value, can be converted into an EUAC using the appropriate annuity factor. Comparing EUAC at different ages reveals whether it is cheaper, on average per year, to retain the machine for a longer period or to replace it earlier (Blank & Tarquin, 2008, pp. 215–235). The same logic applies when comparing machines or acquisition strategies with different initial costs and expected service lives (Blank & Tarquin, 2008, pp. 80–98, 107–118).

2.8.3 Internal rate of return, payback, and other indicators

Internal rate of return is the discount rate at which the net present value of an alternative is zero, representing the effective return generated by an investment (Blank & Tarquin, 2008, pp. 124–151). In an equipment context, IRR can be used to evaluate investment in a new machine or major upgrade by comparing its IRR with a minimum attractive rate of return. If the IRR exceeds this benchmark, the investment is considered acceptable (Blank & Tarquin, 2008, pp. 124–151; Bull, 1993, pp. 3–10).

Payback period measures the time required for cumulative net benefits to recover the initial investment. It is simple to calculate and easy to interpret, which explains its popularity in practice, despite its limitations (Blank & Tarquin, 2008, pp. 124–151; Bull, 1993, pp. 4–6).

However, both IRR and payback have limitations as primary decision criteria. IRR can be misleading when cash-flow patterns are non-conventional, for example when there are multiple changes in cash-flow sign, potentially producing multiple IRRs or no meaningful result. It also does

not indicate the scale of the investment or the absolute value created (Blank & Tarquin, 2008, pp. 124–151). Payback ignores the time value of money and any costs or benefits occurring after the payback point, which can be significant for long-lived equipment or infrastructure (Bull, 1993, pp. 4–6). Consequently, IRR and payback should be used as supplementary indicators rather than as replacements for present-worth or EUAC analysis (Blank & Tarquin, 2008, pp. 124–151; Bull, 1993, pp. 3–10).

2.8.4 Sensitivity and risk analysis in economic decisions

Sensitivity analysis examines how variations in key inputs influence the outcome of economic evaluations. This is particularly important for equipment decisions because many inputs are uncertain. Fuel prices, maintenance-escalation rates, utilization levels, salvage values, and discount rates may deviate from their initial estimates over the equipment's life (Blank & Tarquin, 2008, pp. 182–201; O'Connor, 2014, pp. 1–4).

Sensitivity analysis can be conducted by varying one parameter at a time and observing its effect on present value, EUAC, or economic life. This helps identify which assumptions are most critical to the decision (Blank & Tarquin, 2008, pp. 182–201).

When multiple sources of uncertainty interact, probabilistic methods such as Monte Carlo simulation can be used to model their combined effect on life-cycle cost and replacement timing (Blank & Tarquin, 2008, pp. 182–201; O'Connor, 2014, pp. 1–4). In O'Connor's equipment LCC analysis for public fleets, fuel price and maintenance costs are treated as random variables, and the resulting distribution of total costs is analysed to inform replacement decisions under uncertainty (O'Connor, 2014, pp. 1–4).

2.9 EXISTING LCC MODELS AND FLEET OPTIMIZATION

Defining an equipment LCC model to estimate ownership and operating costs over time, and integrating engineering-economy methods to compare alternatives or determine economic life, is an essential part of life-cycle costing. Fleet-optimization models must consider multiple equipment types and units simultaneously in order to determine the most appropriate fleet mix and replacement strategy for an organization's workload (Gransberg, Popescu, & Ryan, 2006, pp. 19–29, 121–139; O'Connor, 2014, pp. 1–4).

2.9.1 Life-cycle cost models for equipment

Life-cycle cost models for equipment, such as those based on the approaches of Peurifoy and Schexnayder and used by Gransberg and O'Connor, are structured around annual ownership and operating-cost estimates. Ownership costs, including capital recovery, interest, insurance, storage, and taxes, and operating costs, including fuel, maintenance, repairs, tyres, consumables, and labour, are estimated for each year of the asset's expected life. Age-dependent functions are sometimes used to represent the evolution of maintenance and operating costs (Gransberg, Popescu, & Ryan, 2006, pp. 19–29; O'Connor, 2014, pp. 1–4). Salvage value is also estimated for each year, allowing replacement to be analysed at different ages (Blank & Tarquin, 2008, pp. 215–235).

These annual cost streams are then used to calculate present-worth or equivalent-annual-cost values for each prospective replacement age or equipment alternative. In deterministic models, each cost component is treated as a known value. In stochastic models, selected components, such as fuel and maintenance costs, are represented by probability distributions, and the resulting life-cycle cost becomes a random variable (O'Connor, 2014, pp. 1–4).

2.9.2 Optimal equipment replacement models

Optimal equipment-replacement models apply the LCC framework to determine the most appropriate time to replace a machine. Classical deterministic models calculate the EUAC for each possible replacement age and select the age with the minimum cost, assuming fixed cost parameters and a constant discount rate (Blank & Tarquin, 2008, pp. 215–235; Gransberg, Popescu, & Ryan, 2006, pp. 46–64). Marginal analysis can also be used to compare the cost of retaining an asset for one additional year with the cost of replacing it immediately, leading to decision rules such as replacing when the marginal cost exceeds the average annual cost (Blank & Tarquin, 2008, pp. 215–235).

O'Connor extends this approach by recognizing that certain parameters, notably fuel price and maintenance costs, are uncertain and variable. By modelling these parameters as random variables and applying stochastic simulation, this approach estimates a distribution of total life-cycle cost outcomes for different replacement ages, allowing decision-makers to consider both expected cost and risk when defining replacement policies (O'Connor, 2014, pp. 1–4). This highlights the sensitivity of the optimal replacement age to assumptions about uncertain inputs, particularly in

public fleets, where policy and budget constraints may also influence replacement timing (O'Connor, 2014, pp. 1–4; Gransberg, Popescu, & Ryan, 2006, pp. 39–64).

2.9.3 Models for optimal sizing and composition of fleets

Models for optimal fleet sizing and composition seek to determine how many units of each equipment type should be owned, rented, or replaced at each point in time in order to meet anticipated work demands at minimum cost. Mismatched capacities among interdependent machines lead to idle time and inefficiency, while utilization plays a key role in spreading ownership costs (Gransberg, Popescu, & Ryan, 2006, pp. 121–139; Edwards, 2003, pp. 20–27).

From a conceptual perspective, optimal fleet composition depends on the expected mix of projects, such as earthworks-dominated or structures-dominated work, the variability of demand over time, and the availability of rental markets to cover peak requirements or specialized needs. Ownership is generally favoured for high-utilization equipment required across multiple projects, whereas rental may be used to cover temporary peaks or specialized tasks (Gransberg, Popescu, & Ryan, 2006, pp. 19–24, 225–236; Edwards, 2003, pp. 20–27). LCC models can also be applied at fleet level by aggregating costs for different fleet compositions and comparing them over multi-year horizons.

2.9.4 Contractual and procurement criteria based on LCC models

LCC considerations derived from the analytical models discussed above can provide substantial decision support for procurement strategies and contract forms. Ownership-versus-rental decisions, for example, affect the types of contracts entered into by an organization, including purchases with warranties and service agreements, leases with defined terms and residual-value arrangements, or rental agreements specifying rates, minimum periods, and responsibilities for maintenance and damage (Gransberg, Popescu, & Ryan, 2006, pp. 225–236; Edwards, 2003, pp. 23–25). Outsourcing equipment through rental or operated-plant contracts transfers certain risks, such as maintenance, obsolescence, and underutilization, to suppliers, but also embeds life-cycle costs and supplier margins into the hire rates (Edwards, 2003, pp. 23–27).

LCC-based award criteria imply that tenders for equipment, or for design-build projects, should be evaluated on the basis of total discounted cost rather than initial price alone. For example, when procuring a fleet of trucks, a client might compare suppliers according to purchase price, fuel

efficiency, maintenance intervals, and warranty provision, estimating total cost of ownership over a defined horizon (Bull, 1993, pp. 1–10; Gransberg, Popescu, & Ryan, 2006, pp. 19–29). Similarly, in contracts that include equipment provision, owners may favour bidders that demonstrate lower life-cycle costs through more efficient equipment and construction methods.

2.9.5 Identified gaps and research opportunities

The limited treatment of uncertainty in many deterministic LCC and replacement models is a clearly identifiable gap. Parameters such as fuel price, maintenance escalation, utilization, and salvage value are uncertain, yet standard models often treat them as fixed. O'Connor demonstrates that incorporating stochastic variability can materially change recommended replacement policies, particularly in public fleets (O'Connor, 2014, pp. 1–4). There is therefore an opportunity to develop more widely applicable and practical stochastic LCC tools for equipment decisions.

Another gap concerns the integration of operational fleet data with LCC and optimization models. Gransberg, Popescu, and Ryan, as well as Edwards, emphasize the importance of maintenance and operating records and electronic data systems for equipment control. However, they do not fully describe how real-time or high-frequency telemetry data can be systematically incorporated into LCC analyses and fleet-optimization models (Gransberg, Popescu, & Ryan, 2006, pp. 237–256, 293–304; Edwards, 2003, pp. 4, 25–27). This suggests research opportunities in data-driven fleet analytics capable of calibrating cost and reliability models directly from operational data.

A further gap relates to the limited discussion of how public-sector budgeting, procurement rules, and project-appraisal frameworks interact with equipment LCC optimization. Bull discusses life-cycle costing in public infrastructure but does not address the constraints faced by public agencies when capital and operating budgets are separated, or when replacement decisions are subject to political and administrative processes (Bull, 1993, pp. 20–22). There is scope for research on aligning LCC-based equipment management with institutional realities in road authorities and other public bodies.

Finally, although fuel use and maintenance are recognized as cost drivers with environmental implications, there is limited integration of environmental performance or sustainability criteria into equipment LCC models (Bull, 1993, pp. 1–10; O'Connor, 2014, pp. 1–4). Linking LCC analysis with life-cycle environmental assessment, or incorporating environmental prices into LCC, would extend current practice. However, it would require additional environmental data and substantial

methodological development, which is beyond the objectives of this dissertation.

3

CONCEPTUAL FRAMEWORK AND LCC MODEL FOR ROAD-CONSTRUCTION FLEETS

3.1 CONCEPTUAL FRAMEWORK

This chapter defines the conceptual basis and mathematical structure of the equipment LCC model. It presents the definition of system boundaries, cost categories, present-worth and equivalent-annual-cost formulations, economic-life and replacement criteria, fleet-level decision variables and constraints, and the associated performance indicators. The framework follows Bull and, in particular, the work of Gransberg and O'Connor. The financial concepts related to the time value of money are based on Blank and Tarquin (Gransberg, Popescu, & Ryan, 2006, pp. 19–29, 39–46, 163–195, 237–244; O'Connor, 2014, pp. 1–20; Bull, 1993, pp. 1–17, 31–42; Blank & Tarquin, 2008, pp. 80–98, 107–118).

3.1.1 Relationship between equipment management, LCC, and economic decision-making

Equipment life-cycle cost analysis provides a systematic representation of all cash flows generated by a machine from acquisition to disposal. As in many other investment decisions, the acquisition, operation, and eventual disposal of an asset are spread across several years. These cash flows must therefore be assembled into a time-indexed cost function and discounted to a common base year (O'Connor, 2014, pp. 1–3; Bull, 1993, pp. 1–7). As will be seen in the next chapter, the definition of a base year is a crucial starting point in the construction of an LCC model.

The LCC model must include the full cost stream, comprising the initial capital investment, recurring ownership expenses, usage-dependent operating costs, maintenance, repairs, and eventual disposal or asset resale. All these events must be related to a single point in time. Engineering-economy measures, such as present worth and equivalent annual cost, cannot be calculated unless all values are adjusted to the predefined base year (Gransberg, Popescu, & Ryan, 2006, pp. 19–25).

Fleet-management decisions regarding acquisition, replacement timing, or repair strategies generate different cash-flow trajectories and, consequently, different present-worth and equivalent-annual-cost results for each scenario. In decision-support terms, a fleet manager able to compare these metrics directly across scenarios has a clear advantage over one relying only on initial purchase price, service age, or utilization (Blank & Tarquin, 2008, pp. 80–98).

Life-cycle cost methodology therefore establishes a connection between the production perspective and financial decision-making, supported by time-indexed cost comparisons and discounted cash flows (Blank & Tarquin, 2008, pp. 80–98; Bull, 1993, pp. 7–17).

3.1.2 Decision levels: equipment, project, and company

As discussed before, the application of this LCC concept at a three-level structure—machine, project, and fleet—makes it a useful tool to support long-term decisions on fleet composition, replacement policies, acquisition programmes, and rental-versus-ownership strategies under the capital and operational constraints imposed on the company (Gransberg, Popescu, & Ryan, 2006, pp. 225–236; O'Connor, 2014, pp. 10–18).

Taking into consideration the focus on LCC analysis followed in the work, the implementation of the present LCC model will focus essentially on the first two of the existing three levels of analysis:

- At the **equipment level**, LCC will naturally be focused on a unit-by-unit basis, estimating the economic life of each machine and supporting decisions on maintenance, complete overhauling, or simply unit replacement or disposal (Gransberg, Popescu, & Ryan, 2006, pp. 39–46). In economic terms, the criterion for machine replacement consists of calculating the discounted sum of ownership and operating costs minus the discounted salvage value. The LCC model must therefore determine the machine age that minimizes the equivalent annual cost, because this is identified as the economically optimal replacement time, as mentioned before (Blank & Tarquin, 2008, pp. 90–98; O'Connor, 2014, pp. 5–10).

- At the **company or fleet level**, the LCC model will be deployed through a macro-analysis of each distinct class of machines. Despite being quite heterogeneous regarding their own characteristics and cost inputs, this LCC model can still be applied to maintain the same logic of deciding how many units of each type to buy or rent, and when to repair or replace them, under the allocated budget, so that they yield the greatest possible long-term cost-effectiveness.
- At the **project level**, the focus is on machine productivity. As mentioned previously, the case study presented in this work focuses essentially on LCC and machine-replacement strategies. The expected output and related productivity regarding the construction work to be carried out are assumed to be calculated by the project manager or engineering team. The output levels are therefore defined at a previous stage, generating the occupancy, mileage, and fuel consumption that are later analysed by the present LCC model. Cycle-time and productivity calculations, along with machine rates, will define the cost and duration of machine operation while performing the assigned project tasks. This information is essential to define the cost of each type of machine required to perform the planned tasks, which will certainly influence the decision on the construction methods to be deployed (Gransberg, Popescu, & Ryan, 2006, pp. 65–76, 121–139).

3.1.3 Articulation between fleet LCC and project economic appraisal

The life-cycle costing framework for construction emphasizes that infrastructure owners and financiers, such as public authorities, banks and other financiers, and development consortiums, should evaluate projects on the basis of discounted life-cycle costs and benefits rather than initial construction cost alone. This economic appraisal of equipment-intensive infrastructure projects, such as road construction, is essentially conducted at project level through discounted life-cycle cost and cost-benefit analysis, not at the level of individual machines (Bull, 1993, pp. 7–17). At project level, the cost streams generated by the given road-construction project are themselves built upon assumptions of equipment costs, equipment productivity, and reliability, which are determined by fleet LCC management (Gransberg, Popescu, & Ryan, 2006, pp. 121–139).

As seen previously, the goal is to minimize the total discounted cost of providing the required equipment services to all projects over a multi-year planning period, while maintaining acceptable equipment availability and the required service levels (Bull, 1993, pp. 31–42). For example, a fleet strategy that systematically replaces equipment around the economic-life threshold and maintains

high availability will yield lower expected construction unit costs and fewer delays than a strategy that runs equipment far beyond the economic-life threshold, with higher breakdown rates and repair costs (Gransberg, Popescu, & Ryan, 2006, pp. 39–46; O'Connor, 2014, pp. 5–13).

3.2 GENERAL STRUCTURE OF THE LCC MODEL

3.2.1 System boundaries and analysis horizon

The LCC model for equipment is defined over a clear system boundary. The system boundary for the equipment model should include acquisition, all site-independent ownership costs, site-dependent operating costs—fuel, maintenance, tyres, repairs, and operator costs—and disposal or salvage value (Bull, 1993, pp. 7–17). More specifically, the following costs are considered:

- All costs to acquire and commission the machine, including purchase price, options, taxes, transport, and assembly.
- Annual ownership costs, including depreciation, interest on invested capital, insurance, property taxes, storage, and yard costs (Gransberg, Popescu, & Ryan, 2006, pp. 19–25).
- Usage-dependent operating costs, including fuel and lubricants, routine maintenance, corrective repairs, tyres and wear parts, consumables, operator wages and benefits, and mobilization and demobilization (Gransberg, Popescu, & Ryan, 2006, pp. 25–29; O'Connor, 2014, pp. 5–8).
- The economic consequences of downtime, including reduced effective production or the additional standby units required to maintain production (Gransberg, Popescu, & Ryan, 2006, pp. 237–244; O'Connor, 2014, pp. 5–13).
- Salvage or residual value at disposal (Gransberg, Popescu, & Ryan, 2006, pp. 20–21; O'Connor, 2014, pp. 8–13).
- General corporate overheads and user costs, such as road-user delay and accidents, are excluded, as they belong to distinct project-level or network-level cost structures (Bull, 1993, pp. 7–17).

Regarding the analysis horizon, **it** may be set according to the machine's economic-life analysis or according to a policy horizon, such as a 12-year fleet plan, within which several replacements of the same unit may occur (Blank & Tarquin, 2008, pp. 80–98; O'Connor, 2014, pp. 5–10). It can also be

simply attached to the duration of a specific programme of works. For public fleets, O'Connor notes that analysis is often performed machine by machine over potential retention periods—for example, from one to fifteen years—and repeated for multiple assets, with fleet-level decisions emerging by aggregating or ranking these machine-level results (O'Connor, 2014, pp. 5–10).

3.2.2 Definition and categorization of costs

The categorization of costs will follow the framework prescribed by Gransberg et al. (2006), as mentioned in the previous chapter. Essentially, two categories of costs will be considered: ownership costs and operating costs, with the latter category further subdivided into preventive maintenance, corrective maintenance, fuel, and tyre or track replacement.

Along these two categories, equipment acquisition cost, excluding financing costs, and equipment residual value will be considered. As a matter of simplicity, and in order to follow as closely as possible the cost-allocation policy of the company involved in this work's case study, machine-operator costs are assigned to the construction sites, while all other outstanding overheads are assigned directly to the main-office cost centre. Therefore, only costs directly generated in the workshop, such as tools and mechanic wages, will be considered.

3.3 MATHEMATICAL FORMULATION OF LCC

3.3.1 LCC function for an individual equipment unit

For a given replacement age T_k, the present-worth life-cycle cost is:

$$\mathrm{LCC}_k(T_k) = IC_k + \sum_{t=1}^{T_k} (OC_{k,t} + OP_{k,t}) \; - \; S_{k,t}$$

This expression follows the general present-worth formulation for investment alternatives—initial outlay, series of costs, terminal value—as presented in engineering-economy texts and adapted to equipment cost streams (Blank and Tarquin, 2008, pp. 80–90; Gransberg, Popescu, and Ryan, 2006, pp. 39–41; O'Connor, 2014, pp. 5–10). In deterministic analysis, $OC_{k,t}$, $OP_{k,t}$, and S_{k,T_k} are fixed estimates; in stochastic analysis, O'Connor treats some of these as random variables and examines the distribution of $\mathrm{LCC}_k(T_k)$ (O'Connor, 2014, pp. 13–20).

Notation and variables:

For an equipment unit k, over discrete years $t = 0,1, \dots, T_k$:

- IC_k: initial acquisition and commissioning cost.
- $S_{k,t}$: expected salvage value at end of year t.
- $OC_{k,t}$: ownership cost in year t.
- $OP_{k,t}$: operating cost in year t.
- T_k: candidate replacement age (years).

Ownership and Operating costs can be decomposed as:

$$OC_{k,t} = I_{k,t} + S_{k,t} + TAX_{k,t} + ST_{k,t}$$

$$OP_{k,t} = F_{k,t} + M_{k,t} + TY_{k,t} + C_{k,t} + L_{k,t} + MOB_{k,t}$$

Where:

- I = interest,
- INS = insurance,
- TAX = tax,
- ST = storage
- F = fuel/lubricants
- M = maintenance/repairs
- TY = tyres/wear parts
- C = consumables
- L = operator
- MOB = mobilisation (Gransberg, Popescu, and Ryan, 2006, pp. 19–29; O'Connor, 2014, pp. 5–8).

Depreciation is excluded because the formula already includes the acquisition cost; adding depreciation would **double-count** the same capital expenditure.

3.3.2 Equivalent annual cost and cost per unit of production

To compare different replacement ages, the present-worth cost is converted to an equivalent uniform annual cost EUAC_kover T_k using the capital-recovery factor:

$$\mathrm{EUAC}_k(T_k) = \mathrm{LCC}_k(T_k) \cdot i$$

This is standard in replacement analysis and aligns with the approach described by Blank and Tarquin (Blank and Tarquin, 2008, pp. 90–98; Gransberg, Popescu, and Ryan, 2006, pp. 41–46). From EUAC, the following derived indicators are defined:

- **Average cost per operating hour** over the life $c_{k,h}(T_k)$**:**

$$c_{k,h}(T_k) = \frac{\text{Total Operational Costs}}{\text{Total Working Hours}} = \frac{\mathrm{EUAC}_k(T_k)}{\acute{U}_k}, \acute{U}_k = \frac{1}{T_k}\sum_{t=1}^{T_k} U_{k,t}$$

- **Average cost per unit of production** $c_{k,q}(T_k)$:

$$c_{k,q}(T_k) = \frac{\text{Total Operational Costs}}{\text{Total Production Output}} = \frac{\mathrm{EUAC}_k(T_k)}{\acute{Q}_k}, \acute{Q}_k = \frac{1}{T_k}\sum_{t=1}^{T_k} Q_{k,t}$$

  Where:

  - $U_{k,t}$: productive operating hours in year t.
  - $Q_{k,t}$: output produced in year t (e.g. m³ or tonnes).
  - i: real discount rate.

These unit costs are directly usable in project cost estimates and in comparing alternative methods or equipment combinations (Gransberg, Popescu, and Ryan, 2006, pp. 24–25, 121–129).

3.3.3 Aggregation for a heterogeneous fleet

For a subset of equipment K (e.g. all machines considered in the case study), the fleet LCC is:

$$\mathrm{LCC}_{\text{fleet}} = \sum_{k \in K} \mathrm{LCC}_k(T_k)$$

If units are grouped into classes j (e.g. truck class, loader class) with n_j similar units, each class can be represented using a typical unit's LCC multiplied by class size:

$$\mathrm{LCC}_j = n_j \mathrm{LCC}_{\mathrm{rep},j}$$

This simplifies analysis, as done in practical fleet studies and in O'Connor's treatment of public fleets (O'Connor, 2014, pp. 10–15), while still capturing heterogeneity between equipment types.

3.4 ECONOMIC LIFE AND REPLACEMENT RULES

The concepts of economic life, profit life, and physical life are essential milestones for any operating equipment. Any replacement decision will necessarily need to take them into consideration.

Economic life can essentially be defined as the period starting at acquisition and ending at the peak-profit point. By peak profit, we understand the point at which the total revenue generated by machine output, after deducting all other costs incurred until that point, is maximized.

The graph in Figure 1, Equipment Life: Economic versus Profit versus Physical Life, displays a line parallel to the horizontal axis representing the acquisition value and all other expenses required to make the machine reach the break-even point. The moment the output, or revenue, curve surpasses this break-even line marks the effective start of profitability for the equipment's operation. In this example, it is clear that the equipment in question only reached its break-even point at roughly four years of operation.

Profit life is also well illustrated in the graph and can be clearly seen as the period between machine acquisition and the end of profitability, shown by the output curve crossing the break-even line on a downward trajectory. After this point, the machine might still be able to be kept functional, but the increase in its related maintenance and repair costs has already overtaken the revenue generated. Therefore, the machine is no longer operating at a profit.

Finally, there is the concept of **physical life**, extending between acquisition and the moment at which the machine, although still functional, can no longer perform its assignments in a reliable way.

The extension of the physical life will vary greatly depending on the quality and timing of maintenance carried out over time, as well as the operating environment and the intensity of machine usage (Gransberg, Popescu, & Ryan, 2006, pp. 39–46).

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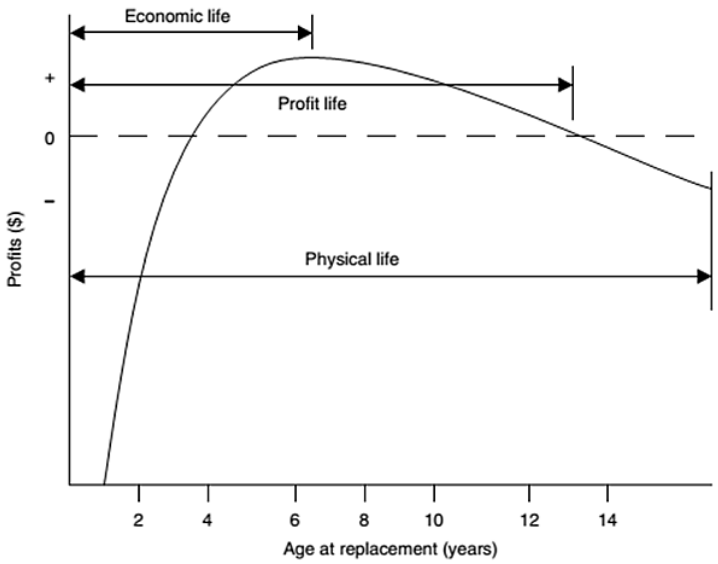


Figure 1: Equipment Life (Economic vs Profit vs Physical Life)
from Douglas J., Construction Equipment Policy, McGraw-Hill 1975

3.4.1 Economic life criterion based on minimum annual cost

Economic life T_k can be obtained by a minimization function where replacement age is the value that minimises the equivalent annual cost of a machine:

$$T_k = arg \min_{T_k \in \{1,\ldots,T_{\max}\}} \mathrm{EUAC}_k(T_k)$$

i.e. the age at which the equivalent annual cost of owning and operating the machine is minimal. Operationally:[3]

- For each candidate age T_k, compute $\mathrm{LCC}_k(T_k)$ and $\mathrm{EUAC}_k(T_k)$.
- Plot or tabulate $\mathrm{EUAC}_k(T_k)$ vs T_k.
- The economic life is at the minimum of this curve.

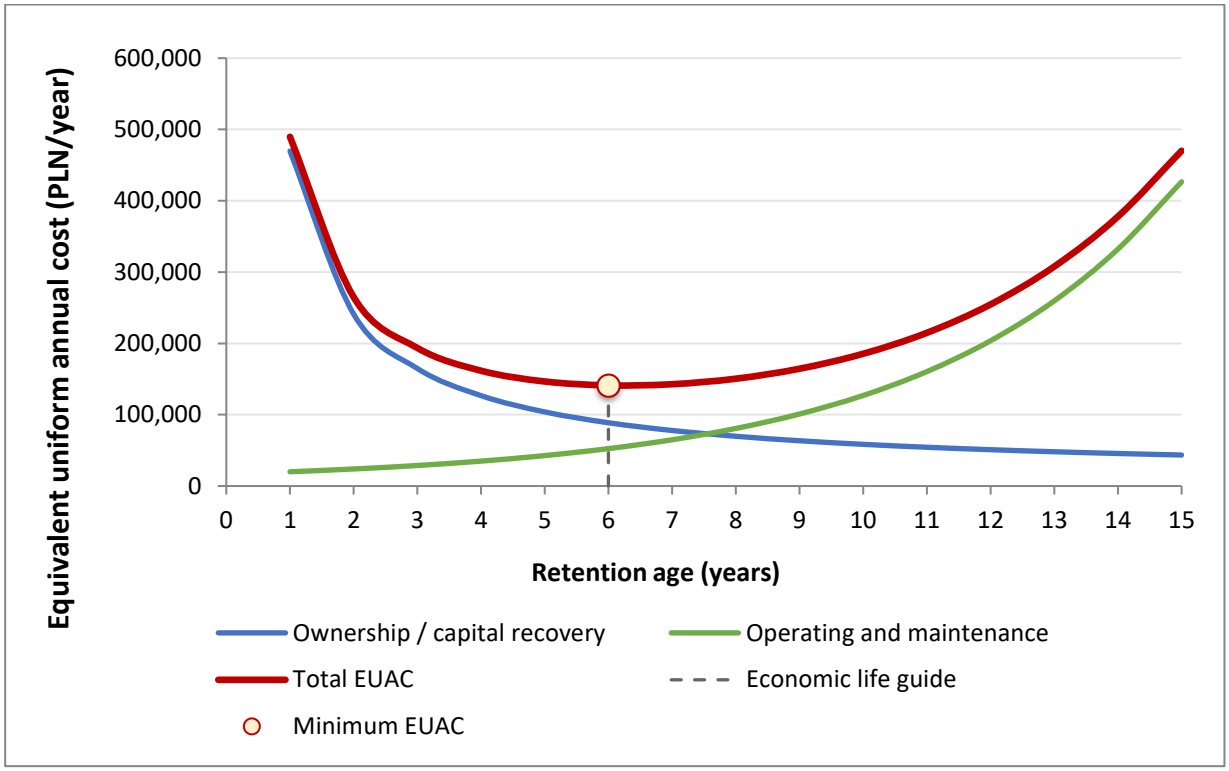


Figure 2: Economic Life of Equipment based on cost minimization

This function translates the profitability trade-off occurring while annual operating cost increases the time (pushed up by higher maintenance and repair costs along with more extensive downtime periods at the workshop), the annual ownership costs decrease with time. (Gransberg, Popescu, and Ryan, 2006, pp. 40–43; Blank and Tarquin, 2008, pp. 90–98).

3.4.2 Replacement decision rules and practical constraints

The theoretical replacement rule is to retire the unit from active duty when it nears the end of its economic life, or when the marginal cost of keeping it one more year exceeds the EUAC of a new machine (Blank & Tarquin, 2008, pp. 90–98; Gransberg, Popescu, & Ryan, 2006, pp. 41–46). As mentioned before, replacement should also be considered when repair costs in a year exceed a given percentage of replacement cost, when availability becomes unacceptable, or when major component failures would require large capital outlays that are uneconomic at the current age (Gransberg, Popescu, & Ryan, 2006, pp. 46–52).

Regarding public fleets, and knowing that most operate under rigid budget and policy constraints, the replacement strategy often relies on ranking equipment by excess cost—the difference between

the cost at the current age and the cost if replaced at economic life—and replacing units as budgets allow, rather than strictly at the economic-life age for all units (O'Connor, 2014, pp. 10–18).

3.4.3 Scenario-based treatment of uncertainty

Uncertainty in fuel prices, maintenance-escalation rates, utilization, and salvage values affects both the level and shape of the LCC and EUAC curves. Instead of the more common and easier-to-apply deterministic approach, O'Connor models key cost components as random variables and uses stochastic simulation to obtain distributions for LCC and economic life. This approach is justified when one takes into consideration that optimal replacement ages may shift significantly under different fuel and repair-cost conditions (O'Connor, 2014, pp. 13–20).

The employment of stochastic simulation methods might prove too cumbersome for some cases, so a deterministic method can still be used with some confidence if a scenario-based variant is considered. The user must therefore define a small number of discrete scenarios for the variables with the highest impact on LCC and EUAC, such as fuel price or maintenance-cost inflation. These variables should be considered in separate scenarios, such as low, medium, and high fuel prices, and optimistic, base, and pessimistic maintenance escalation, so that a more realistic approach than a conventional deterministic model can be reached (Blank & Tarquin, 2008, pp. 107–118). Comparing economic lives and cost levels across these scenarios reveals how robust a proposed replacement policy is and provides upper and lower bounds for decision-making without requiring full probabilistic modelling (O'Connor, 2014, pp. 13–20).

3.5 FLEET OPTIMIZATION PROBLEM

3.5.1 Objective functions

At fleet level, the central objective is to minimize the total life-cycle cost of the fleet segment under study over the planning horizon: $\min_{\{T_k\}}$

Alternative but equivalent objectives are minimizing total EUAC or minimizing average cost per unit of production for the planned works (Blank and Tarquin, 2008, pp. 90–98; O'Connor, 2014, pp. 10–15). For public or owner-operator fleets, due to the already mentioned policy and budget constraints, the problem may be formulated as minimizing discounted cost subject to achieving

specified availability and service-level targets, instead of profit maximization (Bull, 1993, pp. 31–42; O'Connor, 2014, pp. 10–18).

3.5.2 Decision variables (replacement ages, acquisition times, fleet size and composition)

The decision variables include:

- Replacement ages T_k for each unit or for representative units in each class.
- Acquisition times a_k for new units (which year to purchase).
- Fleet size and composition: numbers n_j of each equipment type j to own versus hire over the horizon.

Because machine/fleet age and planning periods are discrete and the number of critical equipment types on a road project isn't too significant, candidate policies can be evaluated using a discrete search over combinations of T_k and acquisition patterns, as opposed to solving a continuous optimisation problem (Gransberg, Popescu, and Ryan, 2006, pp. 41–46; O'Connor, 2014, pp. 10–18). This approach also matches the way more empirical replacement guidelines like "replace trucks at 8 or 10 years", rather observing strict fractional replacement age (e.g. "9 years and 5 months").

3.5.3 Constraints on production, availability, investment, and deadlines

Feasible fleet policies must satisfy:

- **Production constraints**: In each period, the available fleet capacity, adjusted for availability and productivity, must be sufficient to achieve planned production volumes without violating project schedules (Gransberg, Popescu, and Ryan, 2006, pp. 163–195).
- **Availability and reliability constraints**: Aggregate availability and reliability of the fleet must meet or exceed target levels, which may require minimum numbers of units or limitations on average age (Gransberg, Popescu, and Ryan, 2006, pp. 237–244).
- **Investment/budget constraints**: Annual capital expenditure for replacements and acquisitions cannot exceed available funds, necessitating prioritization of replacements and perhaps deferral of economically desirable replacements (O'Connor, 2014, pp. 10–18).
- **Schedule and contractual constraints**: Equipment availability and replacement timing must be compatible with project schedules, mobilization windows, and contractual

conditions such as liquidated damages for delay (Gransberg, Popescu, and Ryan, 2006, pp. 163–195; O'Connor, 2014, pp. 10–18).

These constraints ensure that the cost-optimal fleet policy is also operable in the real project and funding environment.

3.6 PERFORMANCE INDICATORS

3.6.1 Cost indicators (LCC, NPV, EUAC, cost per hour, cost per unit)

From the LCC model, the main cost indicators are Present-worth (LCC) and Net present value (NPV).

Present-worth LCC per machine and for the fleet. The Life Cycle Cost (LCC) is the sum of initial investment (I_0) and the discounted future operational costs (C_t)

$$\mathrm{LCC}_k(T_k) = IC_k + \sum_{t=1}^{T_k}(OC_{k,t} + OP_{k,t}) \; - \; S_{k,t}$$

Net present value (NPV) differences between competing replacement or acquisition policies. To compare a new acquisition or replacement policy against the status quo, calculate the difference in Net Present Value (ΔNPV). Where each NPV is defined as the present value of all inflows minus the present value of all outflows:

$$\Delta NPV = NPV_{New} - NPV_{Existing}$$

Equivalent annual cost per machine and fleet-average EUAC. The EUAC converts the NPV of total costs into a uniform annual series. For machine i, with analysis life $n_i$and discount rate r:

$$EUAC_i = \frac{NPV_i}{\frac{1-(1+r)^{-n_i}}{r}} = NPV_i \times \frac{r}{1-(1+r)^{-n_i}}$$

Here, $NPV_i$is the present value of the machine's costs, net of any residual value or other cost-offsetting cash flows. The denominator is the present-value annuity factor. This produces the uniform annual cost equivalent to the machine's life-cycle NPV.

These are derived directly from the present-worth and annual-worth formulations and correspond to the machine rates and unit-cost metrics used in estimating and in comparing alternative project

methods (Blank and Tarquin, 2008, pp. 90–98; Gransberg, Popescu, and Ryan, 2006, pp. 24–25, 121–129).

3.6.2 Utilization and productivity indicators

These indicators affect cost per hour and cost per unit, because low utilization increases ownership cost per operating hour and low productivity increases cost per unit of output for a given hourly cost (Gransberg, Popescu, and Ryan, 2006, pp. 141–158, 237–244).

Key utilization and productivity indicators include:

- Annual utilization rate $U_{k,t}/U_{\max,t}$, where $U_{\max,t}$ is maximum possible operating hours.
- Average production per operating hour $Q_{k,t}/U_{k,t}$.
- Downtime ratio (downtime hours divided by total calendar hours).

Cost metrics track efficiency per operating unit: cost per operating hour $c_{k,h}$ and cost per unit of output $c_{k,q}$ for each machine or class defined on sub-chapter 3.3.

3.6.3 Risk and robustness indicators

When scenarios or stochastic models are used, risk can be summarized by:

- The range, variance, or standard deviation of LCC and EUAC across scenarios or simulation runs.
- The probability that costs exceed a specified budget threshold.
- Regret measures comparing the cost of a chosen policy with the best policy in each scenario.

These indicators help assess how sensitive fleet policies are to uncertainty in fuel prices, maintenance costs, utilization, and salvage values, and support selection of policies that are acceptable under multiple plausible futures (O'Connor, 2014, pp. 13–20; Blank and Tarquin, 2008, pp. 107–118).

3.6.4 Environmental performance indicators (fuel-based)

Fuel consumption, which is already quantified for operating-cost purposes, can be used to derive approximate environmental indicators. Using standard emission factors, such as kilograms of CO2

per litre of diesel, annual emissions per machine and per unit of output can be estimated. This provides complementary metrics, such as emissions per operating hour or per cubic metre of material moved (Bull, 1993, pp. 17–20; O'Connor, 2014, pp. 13–20).

Although this does not constitute a full environmental life-cycle assessment, it extends the LCC framework with basic environmental-performance information derived from existing model outputs.

4
CASE STUDY, DATA, AND MODEL IMPLEMENTATION

4.1 INTRODUCTION

This thesis is structured around a case study in which an LCC model is applied to a real equipment fleet in an actual construction context. As established before, the main reference for the definition of the LCC model is based essentially on Gransberg's definitions, which explicitly cover life-cycle cost.

The case-study life-cycle cost model will be developed in three stages. First, a deterministic, non-discounted LCC model is constructed to establish a clear and direct baseline from which to easily identify the main cost drivers. Second, the time value of money is introduced by discounting all cash flows to present value, yielding net-present-value estimates for alternative replacement strategies. Third, the model is enhanced through a stochastic approach, in which key cost drivers, such as fuel price, utilization, major repair costs, and residual values, are represented by probability distributions and analysed using Monte Carlo simulation.

This follows O'Connor's approach. O'Connor builds and tests an LCC methodology using detailed historical data for an equipment fleet, combining cost, utilization, and age information to derive economic life and replacement policies. O'Connor's work combines deterministic and stochastic models to evaluate each machine's economic life. This approach provides a methodological template for using real fleet data to calibrate and test LCC models (O'Connor, 2014, pp. xi–xiii, 1–5). Gransberg et al. similarly base their cost and replacement procedures on realistic equipment data rather than relying on purely theoretical conceptions (Gransberg, Popescu, & Ryan, 2006, pp. 19–29, 39–46).

This sequence—from deterministic model to discounted model and later to stochastic modelling—allows straightforward comparisons and provides objective support for equipment-replacement decisions under increasing levels of realism and uncertainty.

4.2 CASE-STUDY CONTEXT

4.2.1 Characterization of the road construction fleet analyzed

This case study focuses on a fleet used in highway, dual-carriageway, and single-carriageway road-construction projects. Considering that this is an academic work, the data have been anonymized. No commercial purposes are pursued with this work, so all brands mentioned here have no affiliation or sponsorship with the author.

The available data start in 2005 and span up to 2018. In order to make the data analysis more concise, only machines for which a replacement age could occur within this time span were selected. This constitutes one of the reasons why most machines selected for this study started operation between 2005 and 2009.

4.2.2 Main activities and production requirements

The main activities considered in this case study are those that are strongly equipment-driven and for which LCC can significantly influence cost and production:

- Earthworks, including cuts and fills, the construction of embankments, and subgrade preparation, using excavators, loaders, bulldozers, trucks, and compactors (Gransberg, Popescu, & Ryan, 2006, pp. 65–80, 84–94).
- Subbase, base, and asphalt-layer construction, using graders, pavers, rollers, and haul trucks (Gransberg, Popescu, & Ryan, 2006, pp. 86–92, 121–129).
- Possible specialized operations, such as stabilization and drainage, in which specific equipment types are used intensively.

4.2.3 Fleet characteristics

The fleet is described using the functional equipment categories and technical attributes commonly established by the construction industry. For the case-study road works, relevant types included were responsible for performing the following tasks:

- Earthmoving and excavating: bulldozers, motoscrappers, wheel loaders, crawler excavators, backhoe loaders and wheel excavators.
- Hauling: hauling trucks and tipper trucks.
- Compaction: steel smooth-drum and (vibratory) rollers.
- Paving and finishing: asphalt pavers.

4.2.4 Case-Study fleet selection

Regarding this case study, since it does not involve forecasting but rather a retrospective life-cycle cost analysis using past data, the quality and abundance of the data take precedence over machine variety or other criteria. The machines included had reliable operation throughout their service years, without significant technical-downtime outliers.

Well-documented historical records on ownership, maintenance, and operating costs must also be available for a considerable time span, ensuring that life-cycle cost estimates and replacement analyses are based on robust empirical evidence or, at least, on well-founded assumptions or extrapolations.

The machines must have an overlapping operation time span so that a more direct and meaningful comparison can be made in the life-cycle cost and replacement analysis. By sharing an overlapping operational time span, **it is also ensured that** the machines are evaluated under broadly similar economic, technological, and operating conditions.

The selected fleet must therefore satisfy two key conditions:

- Reliability, in the sense of stable and mostly well-documented cost and maintenance patterns.
- Data availability, meaning that each equipment type included has sufficient historical records to support robust life-cycle cost estimation and replacement analysis.

Within these constraints, the fleet size and composition are defined so that the resulting dataset is quantifiable and statistically meaningful for the purposes of this thesis.

The original full dataset comprised more than 240 machines, of which 93 were selected as the core study sample based on data completeness, operational reliability, and alignment with the defined selection criteria. Of these, 91 machines started operation in the period between 2005 and 2009, with some even remaining with the new company owner until 2023.

The extended time span that some machines in the fleet can reach—some have service lives approaching two decades—presented a methodological challenge. In academic terms, it was not feasible to compile fully detailed, year-by-year life-cycle data for every machine over a 20-year horizon. After careful consideration, **2009** was selected as the reference **year**, as it offered the most complete and consistent records within the company's workshop system. Consequently, the most granular and reliable cost and maintenance data were obtained for this base year, forming the foundation of the life-cycle cost and replacement analysis.

According to the selection methodology mentioned previously, and seeking to optimize productivity and compatibility between machines for highway-construction duties, the following fleet was assembled:

Table 3: Case Study Fleet Composition

Category	Equipment	Units
Asphalt pavers	Vögele Super 1900	2
Backhoe loaders	JCB 3CX	7
Bulldozers	Komatsu D65 EX	3
Asphalt sprayer trucks	Mercedes-Benz 2528 4×2 with asphalt sprayer	2
Hauling trucks	MAN TGS 18.400 4×2; MAN TGA 18.390 4×2	16
Tipper trucks	MAN TGS 41.440 8×6	21
Crawler excavators	Komatsu PC240 NLC-7	6
Milling machines	Wirtgen 2000DC; Wirtgen W1000F	Extral
Motor graders	Caterpillar 140H	6
Pneumatic-tire rollers	Hamm GRW 18	5
Single-drum vibratory rollers	Hamm 3516; Caterpillar CS583 D	7

Category	Equipment	Units
Tandem vibratory rollers	Hamm HD 130; Hamm HD 110	8
Wheeled excavators	Komatsu PW180-7E0	2
Wheel loaders	Caterpillar 966H; Komatsu WA470-5; Komatsu WA400	6
Total core fleet	**Excluding additional milling machines**	**91**

4.3 Data Sources and Study Period

The dataset employed comprises a broad selection of several types of construction machines, all deployed on the construction of large public-infrastructure projects, including motorways and carriageways. The dataset comes from a mid-sized construction company operating in Eastern Europe from around the mid-1990s until it was acquired by a rival in late 2023.

Priority was given to machines with central roles in road-construction tasks, such as asphalt pavers, soil compactors, and steel rollers, but also motor graders, crawler excavators, bulldozers, and wheel loaders. Alongside the fleet of tipper trucks and hauling trucks, a pair of trucks equipped as asphalt sprayers was added.

The dataset does not include secondary equipment, such as compressors, pumps, generators, or cranes. Specialty machines, such as milling machines, telehandlers, piling machines, and asphalt sprayers, are present in the database but, due to their limited quantities, are included only as supplementary information.

Construction equipment may remain in service for many years. Ideally, a complete life-cycle history would therefore include acquisition, operation, maintenance, replacement, and disposal data for the entire service life of each machine. However, collecting such information for a fleet of more than 240 units, with records extending back to the late 1990s, would have been extremely difficult. In addition, complete 15-year historical records were not available for every equipment unit in the company’s fleet.

A further filtering criterion was therefore applied. After reviewing the available records, the study was limited to machines commissioned between 2005 and 2009. The 2005–2009 period provided a suitable timeframe for comparing machines with broadly similar technological characteristics and expected operating efficiency.

It also ensured that sufficient historical records were available to support the analysis. Restricting the sample to equipment that began operating within the same five-year period also improved the comparability of machine age, accumulated operating hours, maintenance history, and cost trends.

Consequently, the selected sample provided a more reliable basis for evaluating life-cycle costs and replacement decisions. Extending the analysis beyond the period supported by reliable records would have required a greater reliance on estimated values. This could have reduced the consistency of comparisons between machines and weakened the credibility of the resulting LCC and replacement recommendations.

The study period spans from 2005 until 2019. This specific observation period was defined according to the availability of information on acquisition, utilization, maintenance, operating, and financial data. Based on the available information, a consistent fleet of matching road-construction equipment was then defined.

Operational data, such as machine daily fuel consumption, daily working hours, and daily downtime hours, were obtained through telemetry via the company's own telematic system, reporting through a GSM network. Other data related to machine operational performance were extrapolated based on these values.

This operational data reflects the machines' real performance values, which means that there were significant variations in machine yearly working hours, since their activity depends upon project assignments in which there might be no available work for them to perform, or they may be transported between sites or simply inactive due to maintenance or repair interventions.

The costs of repairs and corrective maintenance, as well as preventive maintenance, were obtained from workshop service orders and the company's own internal accounting-system records.

The macroeconomic variables required for the calculation of the LCC components were obtained from official statistical and institutional sources. Asset-specific data, including acquisition dates, purchase values, financing conditions, depreciation, and amortization records, were extracted from the company's accounting records for the relevant period. This combination of external macroeconomic data and internal accounting information provided the basis for reconstructing the historical ownership and operating-cost profiles of the selected equipment.

The dataset relies essentially on the author's own archives, generated from his daily duties, alongside a compilation of data retrieved from workshop records, accounting information, operational records,

and data generated through the company's telematics system. Since the data were obtained from company records and the author's professional archives, the dataset has an empirical basis rather than being a fully scientific source.

4.4 DATA PREPARATION, QUALITY ASSESSMENT AND LIMITATIONS

Data treatment consisted not only in identifying suitable individual machines but also in consolidating records from the available sources and screening the data for missing, duplicated, inconsistent, or anomalous entries.

Given that the company telematic system had been implemented some years prior, operational fleet data, such as daily working hours and daily fuel consumption, were available and mostly reliable for the study period in question. In addition, expenses with ownership costs and machine acquisition amounts, along with their book value after amortization, were also available.

The biggest challenge in data preparation was undoubtedly the maintenance costs. There were essentially workshop records, mostly including service orders with the activity performed, but usually no machine ID assigned or spare-parts invoice attached, and the company's own internal accounting system, where amounts were always present but the item descriptions or their quantities were not reliable. Cross-checking these two information sources was therefore difficult, especially when no common descriptions, amounts, or dates could be identified.

Another common workshop imprecision in recording relates to interventions being categorized as repairs when they were not caused by accidents or machine mishandling, but were simply corrective-maintenance procedures carried out to replace worn-out parts not included in the manufacturer's preventive-maintenance plans.

Tyre-cost data presented additional difficulties during the data-reconstruction process. The available records did not consistently distinguish between tyres replaced as a result of normal wear and those replaced because of unexpected damage. Furthermore, descriptions were often incomplete or inaccurate, and item quantities were frequently omitted. Consequently, an invoice containing only the description "tyre" could not always be reliably attributed to a specific machine, particularly because the fleet included different tyre sizes and wheel configurations whose combinations could produce similar invoice amounts.

These limitations made it difficult to determine the exact number of tyres replaced, identify the affected equipment unit, and distinguish routine tyre consumption from exceptional damage-related

expenditure. Where sufficient supporting information was unavailable, the records were either reconciled using purchase dates, equipment assignments, supplier information, and workshop records, or excluded from machine-level analysis. This procedure reduced the risk of assigning tyre costs incorrectly and ensured that only sufficiently reliable observations were included in the LCC calculations.

Associating and filtering all this information was a painstaking task, since invoicing was performed by administrative staff in the central office with little to no knowledge of the items' characteristics and correct designations. This led to situations in which the same machine, component, service activity, or spare part could appear under different descriptions, abbreviations, or coding conventions.

To illustrate how time-consuming this record reconciliation was, it was frequent to find invoices in the records simply registered as "machine oil," without identifying the oil type, specification, quantity, or equipment concerned. This made it extremely difficult to associate the cost with the correct machine category, let alone a specific machine.

The maintenance records spanning almost 15 years required a huge effort of verification, reconciliation, and standardization before they could be reliably assigned to individual machines and cost categories within the life-cycle cost method. Whenever possible, the replacement of parts had to be cross-checked against the manufacturer's documentation so that a possible distinction between repair and wear replacement could be established.

After the data-collection and reconstruction phase was completed, the available cost records were classified and quantified according to the cost categories defined in the LCC framework. The adopted cost structure was based primarily on the equipment-management and ownership-and-operating-cost framework presented by Gransberg et al. (2006), together with the equipment life-cycle-cost approach developed by O'Connor (2020).

Operating costs were treated separately from ownership and maintenance costs. The principal operating-cost component, in order of magnitude, was fuel, followed by costs related to tyres or tracks, usually bearing or linkage replacements in crawler machines.

The analysis performed did not attempt to forecast future fuel use, maintenance requirements, or operating conditions. Instead, it used the historical consumption and cost information available for each machine during the observed period.

A telematics system implemented across the entire fleet recorded all fuel consumption, which meant that it could be reliably allocated to individual machines and included in the life-cycle cost dataset.

The fuel records were aggregated by accounting at fleet, project, or workshop level; allocation would have been less straightforward, having to rely on recorded operating hours, mileage, equipment class, or some other documented fuel-consumption pattern. Fortunately, fuel-consumption records were fully individualized thanks to the telematics-system logs.

Tyres and tracks are specific to each machine category, so they must be treated as equipment-specific operating consumables with wear intervals that depend heavily on operating intensity, site conditions, machine configuration, and accumulated operating hours or distance travelled. Tyres and tracks represent a significant but non-uniform cost component in transport and construction equipment, so correct allocation of these components to the relevant machine, whenever identification was possible, is critical.

4.5 Operationalization of the LCC Model

The case study focuses on a selected group of the company's road-construction equipment fleet that is critical for earthworks and pavement activities.

The framework is the engineering-economy-based LCC structure introduced in Chapter 2 and developed in Chapters 3, regarding ownership and operating cost modelling, present-worth and equivalent-annual-cost evaluation, economic-life determination, and fleet-level aggregation and constraints. This framework aligns directly with an LCC-based approach because:

- It matches the way equipment costs are decomposed and calculated in Gransberg's cost-of-owning-and-operating chapter and in O'Connor's LCCA (Gransberg, Popescu, and Ryan, 2006, pp. 19–29; O'Connor, 2014, pp. 5–10).
- It uses standard engineering-economy measurements (like present worth, equivalent annual cost, economic life) are widely understood to be objective and transparent when comparing different alternative decision scenarios. (Blank and Tarquin, 2008, pp. 80–98, pp. 107-118).
- It reflects how equipment costs are actually estimated in practice (using machine rates and standard methods such as Peurifoy/Schexnayder and Corps of Engineers schedules) (Gransberg, Popescu, and Ryan, 2006, pp. 29–37; O'Connor, 2014, pp. 5–8).

The total life-cycle cost for each equipment unit was computed as the sum of all cost components over the holding period, discounted to a common price base:

$$LCC = C_{\text{acquisition}} + \sum_{t=1}^{n} \frac{C_{\text{mainP,t}} + C_{\text{maintC,t}} + C_{\text{fuel},t} + C_{\text{tyre/track},t}}{(1+i)^t} - \frac{V_{\text{residual}}}{(1+i)^n}$$

where:

- $C_{\text{acquisition}}$= acquisition cost (purchase price + delivery + commissioning + initial attachments)
- $C_{\text{maintP},t}$= maintenance preventive) cost in year t
- $C_{\text{maintC},t}$= maintenance (corrective) and repairs cost in year t
- $C_{\text{fuel},t}$= fuel cost in year t
- $C_{\text{tyre/track},t}$= tyre and track cost in year t
- $C_{\text{other},t}$= other operating cost in year t
- V_{residual}= residual value at the end of the holding period
- i= discount rate
- n= holding period in years

The equivalent annual cost (EUAC) was then calculated as:

$$EUAC = LCC \times CRF$$

This categorization and formula structure aligns with LCC guidance for engineers and asset managers, which recommends separating initial investment, recurring operating and maintenance costs, and end-of-life values to facilitate comparison between alternatives (Dhillon, 2010; Bull, 1993; International Electrotechnical Commission, 2017; International Organization for Standardization, 2017; Fuller & Petersen, 1995).

4.5.1 Acquisition costs

Acquisition cost included the purchase price recorded in the company's asset register plus any directly attributable costs, such as delivery, commissioning, and other additional fees. These costs were verified against purchase invoices registered in the internal accounting-system logs when

available. As mentioned before (Blank & Tarquin, 2014; Park, 2011), accurate recording of acquisition costs is a fundamental requirement in LCC studies, as these costs form the basis for depreciation and ownership-cost calculations. Therefore, extra effort was taken to cross-check registered values against historical values typically charged for this specific type of equipment.

All costs were considered excluding VAT, since this tax can be deducted by the company according to the applicable Polish tax law.

4.5.2 Preventive Maintenance

Given the time constraints of the study and the incomplete or inconsistent identification of certain invoice records, it was not feasible to conduct a detailed investigation of accounting lists containing thousands of entries, most of which mentioned only a cryptic invoice number.

The analysis therefore relied on the most complete and consistently identifiable records, together with documented estimation and allocation procedures for data that could not be directly attributed to individual equipment units.

After much deliberation, the solution came from the fact that the company's Equipment Department Workshop systematically followed the maintenance schedules prescribed by the respective equipment manufacturers. Preventive-maintenance interventions could consequently be reconstructed according to each machine model, its known service-hour history, and the manufacturer-defined maintenance intervals.

Data regarding fuel expenditure, mileage, and working hours came mostly from the logs of the telematics system installed at the time. Being an almost fully automated process with little human intervention helps explain why the data consistency contained in those logs had surprisingly few problems. That is why these logs became absolutely vital for later identifying the missing or misplaced maintenance entries in the chaotic accounting files and imprecise workshop service orders.

This procedure provided a consistent and traceable estimate of scheduled maintenance expenditure, while reducing dependence on incomplete invoice descriptions and non-standard item designations.

Since the cost of each service kit was available in the archive, it was possible to incorporate this information into a worksheet in which, for each machine, the number of scheduled services at each interval could be determined from the cumulative operating hours. The preventive-maintenance cost

could then simply be obtained as the sum of all event costs over the machine's observed operating period.

The annual preventive-maintenance cost assigned to each machine was therefore a function of its recorded annual operating hours, the manufacturer's service intervals, the cost of the applicable maintenance packages, and the workshop labour requirement. This method allows scheduled maintenance costs to be allocated consistently to individual machines, even where invoice descriptions were incomplete or did not explicitly identify the relevant asset.

For machine i, in year t:

$$PMC_{i,t} = \sum_{s=1}^{S} N_{i,t,s} \left(C_{\text{Pack},i,s} + H_{i,s} \times R_{\text{Labour}} \right)$$

Where:

- $PMC_{i,t}$= preventive-maintenance cost of machine $i$in year t
- s= service-package type or maintenance interval, such as 250 h, 500 h, 1,000 h, or 2,000 h
- $N_{i,t,s}$= number of times that service package is due for machine $i$during year t
- $C_{\text{Pack},i,s}$= cost of the parts, filters, fluids, lubricants, and wear items in that service pack
- $H_{i,s}$= workshop labour hours required for the service
- R_{Labour}= internal workshop labor rate in PLN/hour

The year 2009 was selected as the reference year because, during that period, the author had close contact with the company's equipment department, **having** access to more detailed information concerning scheduled maintenance operations and service-kit costs. The available records from that year provided the most complete and consistent basis for identifying scheduled services, routine inspections, lubricants, filters, and other preventive interventions. Earlier records were less complete or less consistently classified, whereas later records reflected differences in equipment age, utilization, and data-recording practices.

Accordingly, 2009 was established as a practical reference point for estimating preventive-maintenance costs, not as a universal maintenance standard or an indicator of equipment economic life. Where direct cost records were unavailable, the reference values were applied according to each machine's cumulative operating hours. The resulting values were treated as estimated model inputs rather than directly observed costs. This procedure provided a consistent method for incorporating

preventive maintenance into the LCC model while acknowledging the uncertainty associated with the available historical data.

Following this procedure, it was possible to overcome the **aforementioned** incomplete raw workshop-cost records by transforming them into a repeatable, machine-specific preventive-maintenance calculation, especially if the sequence of interventions to occur can be implemented programmatically in a spreadsheet, so that the user can easily trace all recurring preventive-maintenance costs in a **convenient and expedient** way.

4.5.3 Corrective Maintenance and other repair costs

This became the hardest part of the process. Unlike preventive maintenance, corrective maintenance involves repairing a machine after a failure or malfunction, which makes it an event-driven intervention that cannot easily be accounted for or estimated.

As mentioned before, most workshop invoices or accounting entries did not contain sufficient technical detail to link the event performed to a specific machine. Given the large number of entries to be analysed, the operation would have been considerably more complex and time-consuming.

After reconstructing the scheduled preventive-maintenance costs, it was possible to remove those already identified as preventive maintenance, as well as the empty invoices featuring only a price or an unrelated invoice number.

For the remaining workshop records, the author followed a three-stage methodology for cost assignment, essentially inspired by *Life Cycle Costing for Engineers* (Dhillon, 2010). The sequence of operations comprised in this methodology has a hierarchical nature and therefore must always be performed in the following order:

Level 1 – Direct allocation (engineering cost method).

Where repair invoices or workshop records explicitly identified machine i, corrective-maintenance cost was calculated as:

$$C_{i,t}^{\text{corr}} = \sum_{k \in \text{repairs}(i,t)} C_k^{\text{invoice}}$$

The actual repair invoice/workshop record when it identifies the machine.

Level 2 – Comparable-machine estimate (analogous cost method). Where machine-specific records were incomplete, missing costs were estimated from comparable machines of the same model or equipment class and similar age and utilization. The group-level corrective-maintenance rate was:

$$r_g = \frac{\sum_{j=1}^{n_g} C_j^{\text{corr}}}{\sum_{j=1}^{n_g} H_j}$$

and the estimated cost:

$$C_{i,t}^{\text{corr}} = H_{i,t} \times r_g$$

This reflects the analogous cost method, which bases estimates on historical data from similar products or assets, adjusted for differences in size, age, and operating conditions (Dhillon, 2010, pp. 88–90; IEC, 2017, pp. 40–41; ISO, 2017, pp. 15–16).

Level 3 – Category-level estimate (parametric cost method).

Where too few comparable records existed, a category-level corrective-maintenance rate per operating hour was applied:

$$r_{\text{cat}} = \frac{\sum_{m \in \text{category}} C_m^{\text{corr}}}{\sum_{m \in \text{category}} H_m}, C_{i,t}^{\text{corr}} = H_{i,t} \times r_{\text{cat}}$$

Only to be used where there are too few comparable records, use the average corrective-maintenance cost per operating hour for the relevant equipment category, then multiply it by the machine's recorded hours.

This corresponds to the parametric cost method, which uses parameters and variables to develop cost-estimation relationships in the form of equations or unit rates (Dhillon, 2010, pp. 90–92; IEC, 2017, pp. 38–40; ISO, 2017, pp. 16–17).

Example:

Consider a 2018 crawler excavator (machine i) in 2024

with recorded operating hours $H_{i,2024} = 1{,}200$h.

1 – Direct allocation.

Two unplanned repair invoices are available for 2024: $C_1^{\text{invoice}} = 8{,}400$PLN and $C_2^{\text{invoice}} = 3{,}600$PLN.

The corrective-maintenance cost is:

$$C_{i,2024}^{\text{corr}} = 8{,}400 + 3{,}600 = 12{,}000 \text{ PLN}$$

2 – Comparable-machine estimate.

Three comparable excavators (group g) have the following data over the reference period:

Machine A: $C_A^{\text{corr}} = 15{,}000$PLN, $H_A = 1{,}500$h

Machine B: $C_B^{\text{corr}} = 10{,}500$PLN, $H_B = 1{,}200$h

Machine C: $C_C^{\text{corr}} = 12{,}000$PLN, $H_C = 1{,}300$h

The group rate is:

$$r_g = \frac{15{,}000 + 10{,}500 + 12{,}000}{1{,}500 + 1{,}200 + 1{,}300} = \frac{37{,}500}{4{,}000} = 9.375 \text{ PLN/h}$$

The estimated corrective-maintenance cost for machine $i$is:

$$C_{i,2024}^{\text{corr}} = 1{,}200 \times 9.375 = 11{,}250 \text{ PLN}$$

3 – Category-level estimate.

For the entire earthmoving category, total corrective-maintenance cost is PLN 420,000 and total operating hours are 40,000 h. The category rate is:

$$r_{\text{cat}} = \frac{420{,}000}{40{,}000} = 10.5 \text{ PLN/h}$$

The estimated corrective-maintenance cost for machine $i$is:

$$C_{i,2024}^{\text{corr}} = 1{,}200 \times 10.5 = 12{,}600 \text{ PLN}$$

For each machine-year in the database, the available financial records should be reviewed and, if possible, allocated to the corresponding machine. A credible link was established through asset identification, component reference, repair description, date, operating context, or workshop information. Entries that could not be assigned with reasonable confidence were excluded from the individual-machine calculation and documented as a limitation of the underlying records (ISO, 2017).

The three-level cost-assignment procedure provided the base corrective-maintenance expenditure for each machine-year. For future years, an ageing factor was used to account for the assumed increase in repair requirements as equipment accumulates operating hours or kilometres. This approach is informed by Mitchell (1998), who modelled construction-equipment repair costs using cumulative operating hours. However, Mitchell's study does not establish the specific linear equation or coefficient adopted here; these are **modelling assumptions** of the present study.

For machine $i$in year t, the ageing factor was calculated as:

$$AF_{i,t} = 1 + \alpha \frac{U_{i,t-1} + 0.5u_{i,t}}{H_{f(i)}}$$

where $U_{i,t-1}$is cumulative usage at the beginning of the year, $u_{i,t}$is expected usage during the year, $H_{f(i)}$is the reference life adopted for the equipment family, and $\alpha$is the escalation coefficient. The numerator approximates cumulative usage at mid-year, assuming that usage is distributed uniformly throughout the year. Operating hours were used for working equipment and kilometres for truck chassis, with consistent units within each calculation.

The reference-life values were assigned by equipment family and documented in the model's input table. These values were treated as assumptions, informed by general equipment-life guidance where available, rather than as manufacturer-certified lifetimes. The coefficient $\alpha$was set to 2. Consequently, the ageing factor increases linearly from 1 at zero usage to 3 when mid-year cumulative usage reaches the adopted reference life. The reference life therefore acts as a scaling parameter, not as a compulsory replacement limit.

Projected corrective-maintenance expenditure was calculated as:

$$C_{i,t}^{\mathrm{CM,proj}} = C_{i,t}^{\mathrm{CM,base}} \times AF_{i,t}$$

where $C_{i,t}^{\mathrm{CM,base}}$is the base corrective-maintenance cost before the additional ageing allowance, and $C_{i,t}^{\mathrm{CM,proj}}$is the resulting projected expenditure. The adjustment was applied only to base costs that did not already include an equivalent ageing allowance. Verified historical expenditure was retained unchanged to avoid counting the effects of deterioration twice.

The reconstructed maintenance histories provided the observed cost inputs for the life-cycle cost analysis, while the ageing factor supported the estimation of future repair expenditure. Historical expenditure and projected costs were identified separately to distinguish recorded evidence from model-based estimates.

4.5.4 Fuel costs

The telematics system implemented across the entire fleet recorded fuel consumption for each individual machine. Consequently, the fuel records could be reliably assigned to specific equipment units and incorporated directly into the LCC dataset. In contrast, fuel data obtained solely from accounting records would have been aggregated at fleet, project, or workshop level, requiring allocation based on operating hours, mileage, equipment category, or other documented consumption patterns.

Fortunately, the fleet-wide telematics fuel-consumption logs avoided time-consuming manual cost-allocation uncertainties and improved the reliability of the fuel-cost component.

Fuel invoices were not available at workshop level because of the company's own policy to assign fuel costs directly to each construction project's own cost centre. Therefore, fuel costs were calculated based on historical retail prices, excluding VAT, extracted from the EU's own weekly oil bulletins. For each equipment unit, the total fuel cost over the study period was computed as:

$$C_{\mathrm{fuel}} = \sum_{t=1}^{T} \left(Q_{\mathrm{fuel},t} \times P_{\mathrm{fuel},t} \right)$$

where $Q_{\mathrm{fuel},t}$is the fuel quantity consumed in period $t$and $P_{\mathrm{fuel},t}$is the unit fuel price in that period.

Fuel costs are among the largest operating-cost components for off-highway equipment and are commonly expressed on a per-hour basis to enable comparison across machines with different utilization levels (Caterpillar Inc., 2022; Peurifoy & Schexnayder, 2002).

Fuel cost per operating hour was then derived as:

$$c_{\text{fuel,hour}} = \frac{C_{\text{fuel}}}{H_{\text{total}}}$$

where $H_{\text{total}}$is the total operating hours recorded for the equipment over the study period.

For equipment units without direct fuel-consumption data, fuel consumption would have to be estimated using manufacturer specifications, typical consumption rates for the equipment category, and recorded operating hours.

4.5.5 Tyre and track costs

When possible, tyre or track costs were based on actual replacement or refurbishment invoices recorded in the company's accounting and workshop records. For each equipment unit, total tyre and track cost over the study period was computed as:

$$C_{\text{tyre/track}} = \sum_{k=1}^{K} C_{\text{tyre/track},k}$$

where $C_{\text{tyre/track},k}$is the cost of the k-th tyre or track replacement event. Tyre and track cost per operating hour was then derived as:

$$c_{\text{tyre/track,hour}} = \frac{C_{\text{tyre/track}}}{H_{\text{total}}}$$

In cases where a single invoice covered tyre or track replacements for multiple machines, costs were allocated to individual units using pro-rata rules based on the number of tyres or tracks replaced per machine or fleet manager own estimation. As mentioned by (Edwards, 1994; Gransberg, Popescu, & Ryan, 2006) cost-allocation methods for shared resources are necessary for attributing indirect

costs to individual assets. All Workshop records regarding those expenses were therefore verified by the author following those methods.

4.5.6 Residual Value

Residual values for equipment that had been sold during the study period were based, whenever possible, on actual sale prices recorded in the company's disposal files. In all other cases, a flat rate was attributed according to each machine category, typically 20%.

For equipment still in use at the end of the analysis period, residual values were estimated using dealer quotations, second-hand market listings, and standard depreciation curves for construction equipment. In these cases, the estimation can present considerable deviations from one machine to another, depending on second-hand market demand for complete machines or specific parts for later replacement.

Residual-value estimation is a critical element in equipment LCC, as it strongly influences the optimal replacement timing, particularly for high-value assets (Gransberg & O'Connor, 2015; O'Connor, 2014).

The annualised ownership cost for each unit was calculated using the capital recovery factor (CRF) to convert the net capital cost into an equivalent annual amount:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where $i$is the discount rate, $n$is the holding period in years, $C_{\text{acquisition}}$is the acquisition cost, and $V_{\text{residual}}$is the residual value at the end of the holding period. This approach follows standard engineering-economics methods for comparing alternatives with different lives (Blank & Tarquin, 2014; Park, 2011).

If we consider ownership cost on a mere capital recovery perspective the

$$EUAC_{\text{ownership}} = (C_{\text{acquisition}} - V_{\text{residual}}) \times CRF \; = \; C_{\text{ownership}} \times CRF$$

It represents the annual equivalent of the acquisition cost, accounting for the residual value and the time value of money. The difference between the acquisition cost and the residual value of each

equipment unit, representing the net capital cost incurred during the holding period, where $C_{\text{ownership},j}$ is the ownership cost of equipment unit j, $C_{\text{acquisition},j}$ is its acquisition cost, and $V_{\text{residual},j}$ is its residual value at the end of the holding period.

A more holistic approach will consider a broader equipment ownership-cost definition that may also include financing or opportunity cost, insurance, taxes, and storage where it can be considered as the ownership cost:

$$C_{\text{ownership},j} = C_{\text{acquisition},j} + C_{taxesj} + C_{storagej} + C_{insurancej} - V_{\text{residual},j}$$

Where $C_{\text{taxes},j}$, $C_{\text{storage},j}$, $C_{\text{insurance},j}$ $account\ for\ the$ taxes, insurance and storage costs paid during the period ownership period j.

4.5.7 Base Year and Constant-Price Methodology

The study covers equipment operating between 2005 and 2019, with expenditure recorded across multiple calendar years.

Historical nominal costs must be converted to constant prices before comparing years. A cost of PLN 1,000 in 2005 cannot be treated as economically equivalent to PLN 1,000 in 2019. All monetary values must be converted to constant prices using a reference year. This reference year places costs recorded at different dates on a common price basis and removes the effect of general inflation. Consequently, differences in the calculated LCC can be attributed primarily to equipment utilization, age, maintenance requirements, and operating performance rather than to changes in the general price level during the study period (Fuller & Petersen, 1995; Kneifel & Webb, 2020).

Because the preventive-maintenance cost structure was established using reliable company data from 2009, 2009 was selected as the monetary reference year. All historical monetary values were therefore converted into constant 2009 PLN.

All monetary values are therefore expressed in constant 2009 prices, unless otherwise stated. The analysis is retrospective and does not seek to estimate current purchase prices, supplier quotations, or future replacement expenditure. Consequently, any machine-replacement scenario is based on the

cost values used in the current LCC model, which represent equivalent historical values at the 2009 price level.

The conversion was performed separately for each LCC component using the relevant price index or observed supplier-price series. For a cost incurred in year t, the constant-price value was calculated by multiplying the nominal cost by the ratio between the selected component index in 2009 and its value in year t. This procedure preserves the 2009 preventive-maintenance cost baseline while allowing costs incurred in later years to be compared on a consistent monetary basis.

The LCC components were not adjusted using a single general inflation index. Costs were classified according to their economic nature and market exposure, because maintenance labour, machinery, spare parts, tyres, tracks, fuel, and residual values may follow different price dynamics.

Being a registered Polish company operating essentially in the Polish market, component-specific Polish price indices published by Statistics Poland (GUS) had to be used. As in all other EU countries, the HICP or CPI is reserved exclusively for general goods and services and for cost categories for which no other specific deflator could be justified.

Table 4: LCC components specific deflators

LCC component	Preferred approach	Reason
Maintenance labor	Actual workshop labor rates; otherwise, labor-cost or business-service index	Driven by wages, labor shortages, and service-market conditions
Machinery purchase price	Actual acquisition price; otherwise, machinery/equipment producer-price or investment-outlay index	Influenced by manufacturing costs, exchange rates, technology, and supply chains
Spare parts	Supplier invoices; otherwise, closest industrial producer-price category	Parts may follow different markets from complete machinery

LCC component	Preferred approach	Reason
Tyres	Actual supplier prices; otherwise, rubber-product producer-price index	Influenced by rubber, energy, logistics, and specialized tyre demand
Tracks and undercarriage	Actual supplier prices; otherwise, relevant machinery, metal, rubber, or component index	Costs depend on steel, rubber, wear rates, and specialized supply
Fuel	Actual machine-specific expenditure and consumption; otherwise, refined-petroleum index or national diesel-price series.	Strongly affected by crude oil, refining, taxes, and geopolitical conditions
Residual value	Actual sale/trade-in prices or used-equipment market observations	Residual value is a market outcome, not simply the inverse of inflation
General costs	HICP/CPI, where appropriate	More closely related to broad consumer-price movements

If analysing an EU country, Eurostat's industrial PPI measures price changes for goods sold by domestic producers and is available by product and NACE category, making it more appropriate than HICP for machinery and industrial components.

For construction-related costs, Eurostat distinguishes the Construction Cost Index, which reflects input costs, from the Construction Producer Price Index, which reflects prices received for construction output. This component-specific approach avoided applying a general consumer-inflation index to costs whose price behaviour is determined by machinery markets, energy markets, construction inputs, or specialized labour.

Equipment acquisition costs and machinery-related components should be adjusted using the relevant Producer Price Index for machinery and equipment.

Tyres, tracks, spare parts, and maintenance labour were adjusted using the most specific available industrial, service, or supplier-price index.

Usually, fuel costs are adjusted using an index for petroleum products or, where available, the company's actual historical fuel prices. Diesel is affected by crude-oil prices, refining margins, exchange rates, taxation, and fuel-market conditions. In this case, the European Commission's oil-price series reflects this market more directly than general consumer inflation.

Fuel prices must be considered separately where necessary because fuel-price movements tend to differ materially from general inflation. Eurostat identifies diesel and petrol within its HICP-based price statistics, while national and European energy-price databases also provide historical fuel-price series.

The residual value of equipment should not automatically be updated using HICP or the machinery purchase-price index. It should preferably be estimated from:

- Actual sale or trade-in values.
- Dealer quotations.
- Used-equipment market listings.
- Age and operating-hour relationships.
- Machine condition and maintenance history.
- Brand, model, configuration, and technological obsolescence.

A machine may lose value faster than general inflation because of obsolescence, or retain value better than expected because of strong demand in the used-equipment market. Therefore, the residual-value assumption should be tested in the sensitivity analysis.

4.5.8 Real-Cost Approach and Discount-Rate Consistency

Throughout this study, a real-cost approach was adopted. All historical costs were first converted to constant 2009 prices using cost-component-specific indices. The resulting real cash flows were then discounted using a real discount rate.

Alternatively, under a nominal-cost approach, each cost component is forecast using its relevant nominal price-growth rate, including general inflation and any component-specific escalation. These nominal cash flows are then discounted using a nominal discount rate.

Consistency between the cost basis and discount rate is essential. Costs expressed in nominal terms should be discounted using a nominal discount rate, whereas costs expressed in real terms should be discounted using a real discount rate. Inflating costs and subsequently discounting them using a real discount rate is inappropriate unless general inflation has first been removed from the forecast. Otherwise, general inflation may be counted twice, which would distort the life-cycle cost results.

The following expression converts every cost in **constant 2009 prices**, the costs incurred before 2009 are brought forward to 2009 purchasing power and deflate costs incurred after 2009 back to 2009 purchasing power. Or any cost recorded in year t:

$$C_{2009} = C_t \times \frac{I_{2009}}{I_t}$$

Where:

- C_{2009}= cost expressed in constant 2009 prices
- C_t= nominal cost recorded in year t
- I_{2009}= Index value for the reference year, 2009
- I_t= Index value for the year in which the cost occurred

The examples below use the index values from the MACRO table included in the Excel Workbook.

Example 1: Maintenance labor — 2005

Nominal cost in 2005: **PLN 10,000**

Maintenance-labor index in 2005: **29.9**

Maintenance-labor index in 2009: **36.8**

$$10{,}000 \times \frac{36.8}{29.9} = 12{,}307.69$$

Equivalent 2009 cost: PLN 12,307.69.

Example 2: Machinery purchase — 2006

Nominal cost in 2006: **PLN 150,000**

Machinery index in 2006: **57.5**

Machinery index in 2009: **64.9**

$$150{,}000 \times \frac{64.9}{57.5} = 169{,}304.35$$

Equivalent 2009 cost: PLN 169,304.35.

Example 3: Spare parts — 2007

Nominal cost in 2007: **PLN 20,000**

Spare-parts index in 2007: **58.6**

Spare-parts index in 2009: **62.4**

$$20{,}000 \times \frac{62.4}{58.6} = 21{,}296.93$$

Equivalent 2009 cost: PLN 21,296.93

Example 4.

Tracks and undercarriage — 2010

Nominal cost in 2010: **PLN 100,000**

Undercarriage index in 2010: **62.7**

Undercarriage index in 2009: **59.8**

$$100{,}000 \times \frac{59.8}{62.7} = 95{,}374.80$$

Equivalent 2009 cost: PLN 95,374.80

Example 5: Fuel — 2011

- Nominal cost in 2011: **PLN 12,000**
- Fuel index in 2011: **72.4**
- Fuel index in 2009: **57.8**

$$12{,}000 \times \frac{57.8}{72.4} = 9{,}580.11$$

Equivalent 2009 cost: PLN 9,580.11.

Example 6: Residual value — 2012

- Nominal residual value in 2012: **PLN 120,000**
- Residual-value index in 2012: **54.2**
- Residual-value index in 2009: **48.8**

$$120{,}000 \times \frac{48.8}{54.2} = 108{,}044.28$$

Equivalent 2009 cost: PLN 9,580.11.

4.5.9 Discount rate and time value of money

Since all monetary values are being expressed in constant 2009 prices, this implies that the discount rate must exclude general inflation. Therefore, a nominal bank-loan rate cannot be used. Nominal discount rates cannot be applied directly to constant-price cash flows, as doing so would result in an inconsistent treatment of inflation.

A real financial discount rate is therefore required. When we refer to the real discount rate, we are referring to the financial discount rate that reflects the company's opportunity cost of capital or financing cost. There must be no confusion with the social discount rate, which is also mentioned in the EU guidance document and is intended only for public-sector cost-benefit analysis and societal impacts. The financial discount rate of 4% can be used to evaluate equipment-replacement decisions from the perspective of a private road-construction company rather than societal project benefits. The adoption of a real discount rate of 4% per year is consistent with the European Commission's reference parameter for the long-term real opportunity cost of capital.

To assess the robustness of the replacement recommendation, sensitivity analysis can be performed using alternative real discount rates of 2%, 4%, 6%, and 8%.

The company's actual weighted average cost of capital (WACC), obtained directly from the company's own financial records or calculated from its debt cost, tax rate, and equity-cost assumptions, can also be used.

Lastly, if only a nominal bank-loan rate is known as a reference, it must first be converted to a real rate using the Fisher equation:

$$r_{\text{real}} = \frac{1 + r_{\text{nominal}}}{1 + \pi} - 1$$

where:

$r_{\text{nominal}}$is the nominal discount rate;

$\pi$is the relevant expected inflation rate;

$r_{\text{real}}$is the rate used with constant 2009 PLN.

Example

If the nominal company bank loan rate is 9% and expected inflation is 5%:

$$r_{\text{real}} = \frac{1.09}{1.05} - 1 = 3.81\%$$

4.6 SCENARIOS AND DECISION CRITERIA

As discussed previously, the acquisition of new equipment, alongside its maintenance, represents a substantial share of any road-construction firm's cost structure.

The main problem fleet managers face is the timing of machine replacement. If the machine is replaced too late, the maintenance costs and associated downtime periods might outweigh any potential capital-expenditure savings associated with postponing the investment in a new machine acquisition. Therefore, the objective of the model to be defined will be to establish the optimal machine-replacement timing that balances the postponement of new machine acquisition with the minimization of cumulative maintenance costs associated with ageing equipment.

For each possible holding period, the model calculates the equipment's equivalent uniform annual cost (EUAC). The age corresponding to the minimum EUAC is defined as the deterministic economic replacement age:

$$\text{EUAC}_{\text{n}} = PW(LCC_n) \times \frac{r(1+r)^n}{(1+r)^n - 1}$$

The recommended age is for the machine replacement is:

$$a^* = \arg\min_n E[LCC_n]$$

where $n^*$is the recommended replacement age and $EUAC(n)$is the equivalent uniform annual cost for a holding period of $n$years. This age represents the cost-minimising replacement point under the deterministic assumptions adopted in the model.

There are machines that a present a gradually declining EUAC value usually further beyond 10 years. This means the LCC current model cannot capture a specific replacement year because a fixed acquisition cost spread across more and more years is being deducted to flat or insufficiently rising real operating costs. EUAC will therefore keep falling possibly for 20 years or forever.

$$EUAC_n = \underbrace{\left(P - \frac{S_n}{(1+r)^n}\right)(A/P, r, n)}_{\text{capital recovery: tends to fall as } n \text{ rises}} + \underbrace{\text{annualised operating costs}}_{\text{flat or too low}}$$

This situation typically occurs when annual LCC is approximately the same every year, residual value remains positive or decreases gradually, and there are no sufficiently large future repair events or track/tyre overhaul costs. When this happens, the first part falls faster than the second part rises, so EUAC declines.

This brings us to a very important conceptual point that cannot be ignored: from an economic perspective, the costs generated by a machine to perform its work might not, by themselves, justify its replacement. This does not mean the equipment should physically run forever.

That is why, in these cases, replacement analysis should go a step further and introduce a challenger machine scenario, that is, a new equivalent machine to compare with the existing machine, the defender. The challenger machine can still be cheaper on an annual basis, providing the fleet manager with a clear economic reason to replace the existing machine.

The cost of keeping the existing machine must be compared with the estimated lowest EUAC of the potential replacement machine. The optimal replacement age for each machine category or individual machine determined based on LCC model can be defined by calculating for a certain moment in time (for example year *a*) the LCC if the machine is kept and the LCC if the machine is sold or simply disposed of.

For the year *a*, the LCC if the machine is kept must be calculated:

$$LCC_{\text{keep}} = \sum_{t=start}^{a} PV(C_{\text{old},t}) + \sum_{t=a+1}^{T} PV(C_{\text{old},t}) - PV(RV_{\text{old},T})$$

and for the same year a, the LCC if the machine is disposed off and a new one is acquired:

$$LCC_{\text{replace}} = PV(C_{\text{old up to } a}) + PV(C_{\text{new from } a}) - PV(RV_{\text{old},a}) - PV(RV_{\text{new},T})$$

When both values are calculated the following criteria is applied:

$\boldsymbol{LCC_{\text{keep}} < LCC_{\text{replace}}}$ (machine should be kept)
$\boldsymbol{LCC_{\text{keep}} \geq LCC_{\text{replace}}}$ (machine should be replaced during)

Example:

<u>Case 1 – Keep defender (old machine)</u>

Current sale value now: 20,000

Keep 1 more year:

O&M: 8,000

Sale value after 1 year: 14,000

$$i = 10\%$$

$$\text{PW} = 20{,}000 + \frac{8{,}000}{1.1} - \frac{14{,}000}{1.1} = 14{,}546$$

$$\text{EUAC}_{\text{def}} = 14{,}546 \times 1.10 \approx 16{,}000$$

Challenger (new machine, 4-year life)

Purchase: 60,000

O&M: 5,000; 6,000; 7,000; 9,000

Salvage after 4 years: 22,000

$$\text{PW} \approx 65{,}886$$

$$\text{EUAC}_{\text{chal}} \approx 20{,}800$$

Decision: $\mathbf{16,000 < 20,800}$→ Keep defender.

Case 2 – Replace with challenger

Current sale value now: 20,000

Keep 1 more year:

O&M: 18,000

Sale value after 1 year: 12,000

$$i = 10\%$$

$$\text{PW} = 20{,}000 + \frac{18{,}000}{1.1} - \frac{12{,}000}{1.1} = 25{,}455$$

$$\text{EUAC}_{\text{def}} = 25{,}455 \times 1.10 \approx 28{,}000$$

Challenger (same as above): $\text{EUAC}_{\text{chal}} \approx 20{,}800$

Decision: 28.000 >$\mathbf{20,800}$→ Acquire the Chalenger

4.7 COMPUTATIONAL IMPLEMENTATION

The computational tools required for this type of analysis can be purchased or leased from specialised ERP software providers or, in some cases, obtained directly from equipment manufacturers. Nevertheless, the most common solution—particularly among small and medium-sized enterprises (SMEs)—remains the widespread spreadsheet application Microsoft Excel. Excel is also widely used in large enterprises by managers and boards of directors, who are generally less concerned with the technical complexity of specialised ERP systems.

Blank and Tarquin recommend spreadsheets for implementing present-worth, annual-worth and replacement analyses because they support explicit formulas, time series and scenario analysis

(Blank & Tarquin, 2008, pp. 107–118). Similarly, O'Connor's LCC methodology requires computational tools capable of performing stochastic and sensitivity analyses (O'Connor, 2014, pp. 13–20). Edwards and Gransberg also emphasise the importance of robust data records and management information systems for monitoring operational performance and costs (Edwards, 2003, pp. 17–27; Gransberg, Popescu, & Ryan, 2006, pp. 293–301).

4.7.1 Modelling environment and software tools

The fleet database consists of five interconnected sub-databases: fleet composition, utilisation hours, availability hours, fuel consumption, and maintenance and repair costs. These databases provide the input data required for the LCC model and support the calculation of ownership, operating and maintenance costs for each machine.

The data are processed in a Microsoft Excel 2024 workbook, in which costs are compiled using `SUMIF` and `SUMPRODUCT` functions. Excel 2024 was selected because it provides the functionalities required for a scalable LCC calculation model, including modern lookup functions, data-validation tools, conditional formatting and Power Query integration.

Data can be inserted into the workbook through several methods, depending on the data source, update frequency and available system integration. The preferred method is a direct connection between the Excel workbook and the company database, telematics platform or fleet-management system. A direct connection reduces manual intervention, minimises transcription errors and allows the workbook to be refreshed whenever new operational or cost data become available.

Where a direct database connection is not available, data may be extracted from the source system into pre-configured CSV files and inserted into the workbook manually through copy-and-paste. This method is particularly useful when the telematics provider, accounting system or maintenance database does not support a direct Excel connection or when data must first be reviewed and validated by the user. To reduce errors, the CSV files should follow a standardised structure, with fixed column names, consistent date formats, machine identifiers and cost categories.

Power Query can also be used to import, clean and transform CSV files or database extracts before the data are loaded into the calculation worksheets. This approach allows repeated import steps to be saved as refreshable queries, reducing the need for manual data preparation. Other possible methods include connections to cloud-based data sources, application programming interfaces (APIs), shared network folders, OneDrive or SharePoint files, and manual entry for exceptional

records or missing historical data. The selected method should balance automation, data quality, traceability and the technical capabilities of the source systems.

The workbook was designed to be scalable. Formulas were structured so that new machines or additional working periods could be added by copying existing rows or columns, without inserting new formulas or editing existing ones. Drop-down menus, conditional formatting and lookup functions were used to standardise input, improve readability and retrieve machine-specific parameters and dashboard images. The workbook also supports forecast calculations through a Monte Carlo add-in (O'Connor, 2014).

Preference was given to a one-time-payment software package rather than a subscription-based licence. Microsoft Excel 2024 was therefore selected because it is available as a perpetual, one-time-purchase licence, providing predictable long-term software costs and avoiding dependence on annual subscription renewals (Microsoft, n.d.-d). Although this licensing model does not automatically include future major-version upgrades, it was considered more appropriate for an SME-oriented LCC tool because it provides a stable calculation environment and lower recurring costs.

Although alternative spreadsheet packages exist, Microsoft Excel was selected because it offers the most mature integration with Power BI, Power Query and DAX. LibreOffice Calc provides spreadsheet, pivot-table and pivot-chart functionality however, its capabilities for developing highly automated Excel-based LCC models and integrated Power BI dashboards remain more limited. For this reason, Excel 2024 was used as the LCC calculation environment, while Power BI was used for interactive visualisation, filtering and alerting.

The Power BI dashboard enables users to filter the results by machine, working year or year-on-year period and presents them together with relevant alerts and warnings. This architecture allows managers to move from static LCC calculations to an interactive decision-support environment (Microsoft, 2026a, 2026b, 2026d).

The technical implementation of the workbook, including the Excel functions, cell-referencing approach, data-validation rules, conditional-formatting rules and additional Excel 2024 functions considered for future development, is presented in Appendix 1

4.7.2 Structure of spreadsheets, formulas, and possible macros

The spreadsheet structure follows, as closely as possible, the workflow required to produce a detailed and substantiated fleet-analysis report. This report is intended to serve as the main decision-support tool for machine-replacement decisions and other investment allocations (Gransberg, Popescu, & Ryan, 2006, pp. 293–301).

The workbook contains several worksheets arranged from left to right in an approximately chronological sequence.

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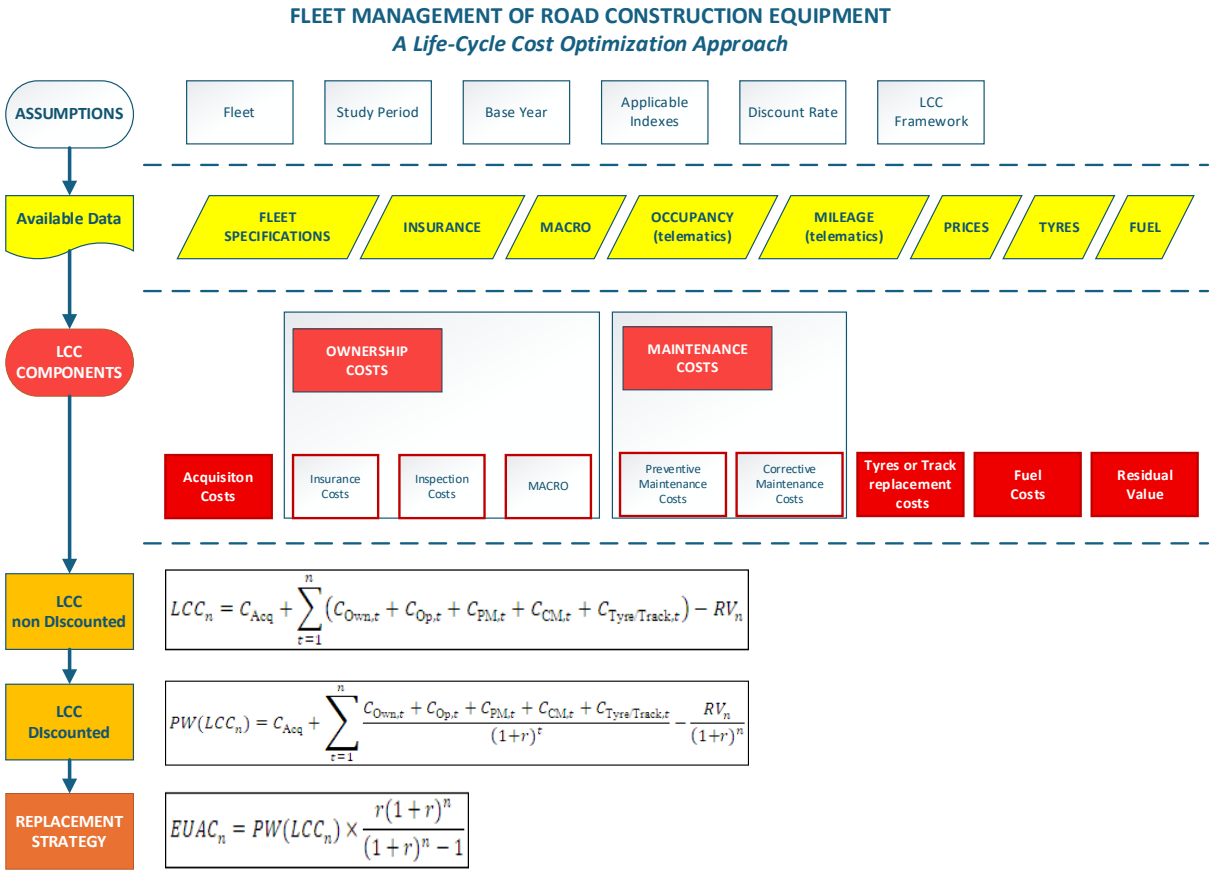


Figure 3: LCC model calculation workflow

The first worksheets, **identified by light-yellow tabs**, contain fleet-inventory information and insurance costs. The third yellow tab contains **the** relevant macroeconomic data, including average annual fuel and oil prices based on official weekly values, currency-exchange rates, inflation and other financial and monetary indices.

The following tabs contain data retrieved directly from the telematics system. The next two worksheets, *Occupancy* and *Mileage*, contain information on occupancy, mileage, average speeds and fuel consumption. This information was obtained directly from the telematics system.

The **final** yellow worksheets contain prices for maintenance events, tyre and track replacement or renewal, and additional fuel-consumption information.

The next two worksheets, **identified by red tabs**, form the core of the ownership-cost calculation process. The ownership tabs calculate all relevant ownership costs, including financing costs through bank loans or leasing arrangements where required. The following two red worksheets, *HE* and *TR*, process the maintenance-cost calculations, including preventive-maintenance costs based on labour and parts.

In addition to maintenance events, fuel consumption and tyre wear or track replacement are automatically included according to the period defined by the user. These worksheets contain highly interconnected cells and use a cost-allocation algorithm; therefore, manual editing of the calculation cells should be avoided.

The orange tabs contain the LCC model calculations, in both non-discounted and discounted versions. Subtotals are presented for each machine, allowing the user to identify intuitively which cost components have the greatest effect on total cost. These worksheets include a drop-down menu in the upper-left corner, allowing the user to select the period to be analysed.

The dark-orange tab contains the replacement-decision algorithm based on the Equivalent Uniform Annual Cost (EUAC) method. The annual EUAC is calculated simultaneously for each machine, allowing any machine to be analysed individually. A warning is displayed to alert the user to the most favourable replacement timing (Blank & Tarquin, 2008, pp. 107–118).

Finally, the black tab contains the stochastic analysis. Variables with a significant impact on the results—such as the discount or financing rate, resale value and fuel consumption—are analysed using triangular distributions. Their effect on total LCC is then compared with the deterministic discounted-LCC result (O'Connor, 2014, pp. 13–20).

4.7.3 Use of advanced Excel spreadsheet functionalities like Power Query

Modern versions of Microsoft Excel, including Excel 2016 and later, include Power Query, an advanced data-transformation tool that can merge tables, clean records and restructure wide datasets

into long tables. Before loading data into the LCC model, the data should be unpivoted, as DAX performs more efficiently with long tables than with wide summary tables (Microsoft, 2026b).

Microsoft Excel with Power BI functionality uses DAX (Data Analysis Expressions) to perform aggregations dynamically. This capability keeps the dashboard responsive even when it processes thousands of records. Unlike cell-based Excel formulas, which generally refer to individual cells (for example, `A1+B1`), DAX references entire columns or tables. (Microsoft, 2026b).

4.7.4 Development of dashboards for Fleet Management

The technical roadmap for spreadsheet development and dashboard design should begin with a clearly defined set of functions aligned with the fleet-management requirements. Accordingly, the following features were identified as essential for the proposed system.

Excel may be used as the input and data-preparation environment, while the Power BI Service provides cloud-based access to interactive reports and dashboards. Power BI supports refreshable connections between Microsoft Excel files and Power BI semantic models, subject to the applicable Microsoft 365 configuration and user permissions. The platform also enables access control through workspace roles and application permissions, allowing different levels of viewing, editing and administration rights (Microsoft, 2026a; Microsoft, 2026c).

The dashboard solution developed in this study is intended to be made available through an embedded Power BI application or configured access point at fleetdashboard.eu. This access point is therefore proposed as the entry point for the fleet-management dashboard, subject to the technical configuration of the hosting environment, Microsoft licensing requirements, user authentication and the protection of confidential company information. Publishing a dashboard externally should not be interpreted as making it automatically available to the public; access must be configured according to the intended user groups and security requirements (Microsoft, 2026d).

The dashboard should provide users with numerical indicators and graphical visualisations of the main financial and operational variables, including revenue, operating hours, maintenance costs, fuel costs, tyre and track costs, taxes, depreciation and repair expenditure. Users should be able to define the analysis period so that the selected indicators and visualisations can be examined over a chosen timeframe.

The system should also allow users to filter the analysis by equipment category or select an individual machine. Based on the selected filters, the dashboard should display the evolution of the relevant performance and cost indicators over time. This functionality would allow managers to compare equipment categories, identify cost trends and investigate the historical performance of individual assets.

A further requirement is the inclusion of a replacement-analysis module for each machine. This module should support evaluation using the Equivalent Uniform Annual Cost (EUAC) method and, where appropriate, a revenue-based method comparing equipment life-cycle costs with the revenue generated by the asset. Under the EUAC approach, alternative replacement cycles are compared by converting their discounted life-cycle costs into an equivalent annual amount (Blank & Tarquin, 2008, pp. 107–118).

The module should allow replacement analysis to be performed for an individual machine or, where appropriate, for a selected equipment category. It should display the EUAC values for each potential replacement year or operating-hour threshold and identify the lowest value. It should also present the corresponding NPV, annual operating and maintenance costs, residual value and replacement recommendation.

The dashboard should therefore include an option to perform replacement analysis for each machine using either the EUAC method or the revenue-based method. As discussed previously, a minimum EUAC may not always exist. In some cases, the calculated EUAC may continue to decrease throughout the analysed period without displaying a clear minimum, owing to stable operating costs, insufficient maintenance-cost escalation or a limited observation period.

If the EUAC analysis does not identify a clear minimum within the evaluated replacement horizon, the dashboard should offer a challenger–defender comparison. The existing machine should be treated as the defender, while the proposed replacement should be treated as the challenger. The comparison should evaluate the defender's marginal cost of retaining the machine for an additional period against the challenger's minimum EUAC. If the defender's marginal cost of retention exceeds the challenger's equivalent annual cost, the system should identify replacement as economically preferable, subject to operational, availability and investment constraints (Blank & Tarquin, 2008, pp. 107–118).

Where sufficient financial and operational data are available, the dashboard should provide a cost-comparison and NPV-analysis module for machines approaching the end of their economically

viable service period. This module should compare the main available alternatives: purchasing a new replacement machine, renting equivalent equipment or acquiring the equipment through a leasing agreement. For each alternative, the analysis should include the relevant initial investment or contractual payments, financing costs, operating and maintenance costs, residual value, taxes and other applicable cash flows over a common evaluation horizon. The alternatives should then be compared using NPV, provided that equivalent service levels are achieved. This functionality would support a more comprehensive replacement decision by combining life-cycle cost, financing and operational considerations (Blank & Tarquin, 2008, pp. 107–118).

Finally, the system requires automation mechanisms that display alerts whenever a predefined variable **exceeds, or falls below,** a specified threshold.

4.7.5 Implementation of Alerts through dashboard KPIs

Alert configuration consists of defining specific visual elements, such as a *Current Maintenance Cost* card, and pinning them to a dashboard in the Power BI Service. Once a visual has been pinned, the user can select the ellipsis on the tile and choose **Manage alerts**. This option enables email notifications when the value displayed in the tile crosses a defined threshold. Where the Excel workbook is stored on a local drive or another data source that is not directly accessible from the cloud, the dataset must be connected through an on-premises data gateway. This connection allows the Power BI Service to refresh the data and evaluate the configured thresholds automatically (Microsoft, 2026e; Microsoft, 2026f).

Power BI data alerts operate at the visual or KPI level and are available only for supported dashboard tiles, such as cards, KPIs, and gauges. They do not automatically evaluate every row of a detailed machine-level table. Therefore, for machine-level alerts, threshold conditions should be calculated in Excel or Power Query and stored in a dedicated alert table. Power BI can then display these alerts and filter them by machine, indicator, severity, and date. Where automatic email notifications are required for individual machines, Power Automate can be used after a scheduled dataset refresh (Microsoft, 2026e).

The system should include automated alert mechanisms that notify users whenever a predefined variable exceeds or falls below a specified threshold. Alerts should be linked to clearly defined fleet-management indicators and should identify the affected machine, variable, threshold, date, and severity level

.

Possible alert conditions include:

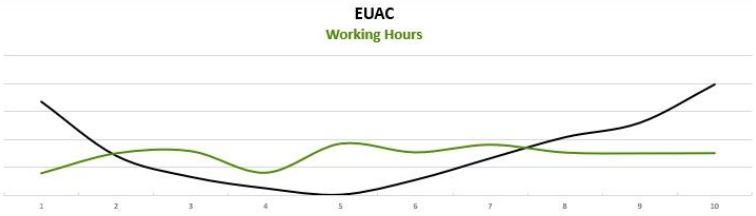
- Maintenance cost per operating hour exceeding a defined limit.
- Fuel consumption exceeding the expected value for the machine category.
- Repair costs increasing above a specified age- or hour-based threshold.
- Operating hours exceeding the planned utilisation level.
- Repeated corrective-repair events within a defined period.
- Downtime or unavailability exceeding the permitted limit.
- Tyre or track costs exceeding the expected replacement rate.
- The defender's marginal cost of retention exceeding the challenger's equivalent uniform annual cost.
- A machine reaching a predefined replacement-decision threshold.
- Missing, inconsistent, or unclassified records requiring data validation.

Alerts are most useful when they connect utilisation, fuel, maintenance and cost indicators to a defined management action, rather than merely reporting that an abnormal value has been detected.

To increase managerial value, the dashboard can be extended with drill-through pages, benchmarking indicators, and an action-priority view. Drill-through enables users to move from a fleet-level KPI to the detailed cost, utilisation, maintenance, and replacement profile of an individual machine. Benchmarking compares actual performance against budgeted, planned, or historical targets, while the action-priority view ranks machines according to cost deviations, alert severity, and replacement urgency. These features transform the dashboard from a monitoring tool into a decision-support system that supports maintenance planning, budget control, and fleet-replacement decisions.

DASHBOARD





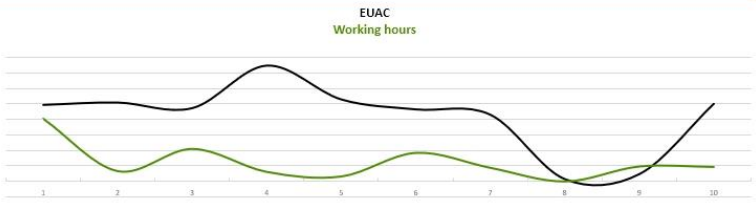
Komatsu D65 EX	BULL01	YEARS:	1	2	3	4	5	6	7	8	9	10
Buldozer												
Acquisiton Year: 2005		EUAC:	733,282	465,939	361,296	305,019	273,570	346,689	453,245	557,579	628,996	791,244
Recommended Year to Replace Machine: 2009												
Acquisition Cost:	775,995 PLN	Book Value:	775,995									
Machine disposal cost:	10,000 PLN	CashFlows:	96,902	118,703	198,752	92,188	125,763	99,567	160,391	95,753	95,235	93,438
Expected Resale Value:	155,199 PLN	Residual Value:	139,614	134,245	129,081	124,117	119,343	114,753	110,339	106,095	102,015	98,091
Total Working hours:	15,807 hours	Working Hours:	955	1,639	1,715	974	1,970	1,671	1,936	1,666	1,638	1,644
Odometer:	19,328 hours											
Fuel Consumption cost since new:	244,420 liters	Consumption:	11,778	20,213	21,147	12,011	24,302	20,613	23,872	20,542	20,197	20,277
Average fuel consumption (per hour):	12.65 liters/hour											
Fuel Cost since new:	726,308 PLN	Fuel Cost:	32,142	54,022	51,971	32,862	69,072	56,210	74,337	75,995	74,639	72,062
Average fuel consumption cost (per hour):	37.58 liters/hour											
Preventive Maintenance Cost since new:	109,471 PLN	Preventive Cost:	2,124	9,553	10,999	6,727	10,999	10,999	11,338	9,553	6,735	9,553
Average preventive maintenance cost (per hour)	5.66 PLN/hour											
Corrective Maintenance Cost since new:	53,333 PLN	Corrective Cost:	0	1,522	4,574	6,937	6,937	5,411	2,053	2,143	5,085	5,877
Average corrective maintenance cost (per hour)	2.76 PLN/hour											

ALERT: FUEL CONSUMPTION TOO HIGH. PLEASE CHECK FUEL DATA.

Figure 4: Fleet Management Power BI Dashboard with excessive fuel consumption alert activated

DASHBOARD





MAN TGS 41.440 8X6	TT01	YEARS:	1	2	3	4	5	6	7	8	9	10
Tipper truck												
Acquisiton Year: 2009		EUAC:	521,396	522,850	519,386	545,693	524,766	518,616	515,340	475,494	478,587	474,621
Recommended Year to Replace Machine: 2018												
Acquisition Cost:	527,798 PLN	Book Value:	527,798									
Machine disposal cost:	10,000 PLN	CashFlows:	85,482	83,402	76,540	99,579	75,511	66,340	60,160	17,520	17,928	11,380
Expected Resale Value:	105,560 PLN	Residual Value:	91,884	88,350	84,952	81,685	78,543	75,522	72,617	69,824	67,139	64,557
Total Working hours:	184,358 Km	Working Hours:	26,728	16,748	20,981	16,603	15,728	20,226	17,382	14,783	17,634	17,546
Odometer:	198,004 Km											
Fuel Consumption cost since new:	66,748 liters	Consumption:	5,583	6,994	5,534	5,243	6,742	5,794	4,928	5,878	5,849	0
Average fuel consumption (per 100Km):	33.71 liters/100Km											
Fuel Cost since new:	193,481 PLN	Fuel Cost:	15,867	19,071	17,234	19,396	24,915	20,591	15,435	15,969	15,331	0
Average fuel consumption cost (per 100Km):	97.72 PLN/100Km											
Preventive Maintenance Cost since new:	15,433 PLN	Preventive Cost:	1,765	1,765	1,832	0	4,575	1,832	1,832	0	0	1,832
Average preventive maintenance cost (per 100Km)	7.79 PLN/100Km											
Corrective Maintenance Cost since new:	49,766 PLN	Corrective Cost:	5,323	5,323	5,470	4,066	4,066	2,961	2,961	3,251	5,470	10,875
Average corrective maintenance cost (per 100Km)	25.13 PLN/100Km											

WARNING: TRUCK SHOULD BE CONSIDERED FOR REPLACEMENT

Figure 5: Fleet Management Power BI Dashboard with warning for approaching decision on Machine replacement

5
RESULTS, DISCUSSION, AND CONCLUSIONS

5.1 INTRODUCTION

This chapter presents the results obtained from applying the deterministic life-cycle cost model to the road-construction equipment fleet. The analysis covers 91 machines distributed across eleven equipment categories: asphalt paving equipment, backhoe loaders, bulldozers, heavy transport and hauling trucks, tipper trucks, crawler excavators, motor graders, single-drum soil compactors, tandem vibratory rollers, wheel excavators, and wheel loaders.

The chapter analyses the contribution of the principal LCC components, including preventive maintenance, corrective maintenance, other repairs, ownership cost, fuel, tyres or tracks, other operating costs, and downtime. It then evaluates the equivalent uniform annual cost for successive holding periods in order to identify the deterministic economic replacement age for each machine or equipment category. The results are subsequently interpreted in relation to the research questions and hypotheses.

Because the calculations are based on company records, archived service-kit prices, operating-hour data, and estimated values where records were incomplete, the results must be interpreted according to the distinction between observed and estimated costs established in Chapter 4.

5.2 DESCRIPTION OF THE CASE STUDY FLEET

The case-study fleet comprises 91 equipment units across eleven categories. Heavy transport and tipper trucks represent the largest group, with 21 units, followed by hauling trucks with 16 units and tandem vibratory rollers with 8 units, along with single-drum soil compactors with 7 units. Backhoe loaders and wheel loaders each account for nine units, while motor graders account for eight units. The remaining categories include crawler excavators, bulldozers, tandem vibratory rollers, asphalt paving equipment, and wheeled excavators.

Table 5: Fleet composition by equipment family

Equipment family	Main models	Units	Utilisation measure	Included in LCC
Asphalt pavers	Vögele Super 1900	2	Operating hours	Yes
Backhoe loaders	JCB 3CX	7	Operating hours	Yes
Bulldozers	Komatsu D65 EX	3	Operating hours	Yes
Crawler excavators	Komatsu PC240 NLC-7	6	Operating hours	Yes
Motor graders	Caterpillar 140H	6	Operating hours	Yes
Pneumatic tyre rollers	Hamm GRW 18	5	Operating hours	Yes
Single-drum soil compactors	Hamm 3516; Caterpillar CS583 D	7	Operating hours	Yes
Tandem drum compactors	Hamm HD 130; Hamm HD 110	8	Operating hours	Yes
Wheeled excavators	Komatsu PW180-7E0	2	Operating hours	Yes
Wheel loaders	Caterpillar 966H; Komatsu WA470-5; Komatsu WA400	6	Operating hours	Yes
Heavy equipment subtotal		**52**	Operating hours	
Asphalt sprayer trucks	Mercedes-Benz 2528 4×2 with asphalt sprayer	2	Kilometres	Yes

Equipment family	Main models	Units	Utilisation measure	Included in LCC
Hauling trucks	MAN TGS 18.400 4×2; MAN TGA 18.390 4×2	16	Kilometres	Yes
Tipper trucks	MAN TGS 41.440 8×6	21	Kilometres	Yes
Truck subtotal		**39**	Kilometres	
Total fleet		**91**		

The fleet is heterogeneous in terms of machine type, manufacturer, technical configuration, operating function, age, and accumulated operating hours. Consequently, total LCC values should not be compared without considering fleet size and utilization. Category-level comparison should therefore use total LCC, average LCC per unit, and LCC per operating hour.

A 10-year analysis period was adopted in order to achieve a more consistent analysis that makes broader use of the available historical dataset on maintenance, fuel, tyre and track, and residual-value effects, with a long horizon to capture the main ownership and operating-cost drivers of the road-construction fleet.

5.3 Calculation of Life-Cycle Cost Components

For each equipment unit, the model calculated the following cost components:

1. Ownership costs
2. Preventive maintenance costs
3. Corrective maintenance and other repairs
4. Fuel.
5. Tyres or tracks.
6. Residual value as a deduction from total cost.

The undiscounted cost structure for equipment unit j was expressed as:

$$LCC_j = C_{OWN,j} + C_{PM,j} + C_{CM,j} + C_{FUEL,j} + C_{T/T,j} - V_{RES,j}$$

where:

- $C_{PM,j}$is preventive-maintenance cost;
- $C_{CM,j}$is corrective-maintenance cost and other repairs;
- $C_{OWN,j}$is ownership cost;
- $C_{FUEL,j}$is fuel cost;
- $C_{T/T,j}$is tyre or track cost;
- $V_{RES,j}$is residual value.

Where costs occurred in different periods, the discounted LCC was calculated as:

$$LCC_j = C_{OWN,j} + \sum_{t=1}^{n} \frac{C_{PM,j,t} + C_{CM,j,t} + C_{FUEL,j,t} + C_{T/T,j,t}}{(1+i)^t} - \frac{V_{RES,j}}{(1+i)^n}$$

The cost per operating hour was calculated as:

$$LCC_{\text{hour},j} = \frac{LCC_j}{H_j}$$

where $H_j$is the accumulated operating time of unit j.

The following table cover timeframe on years 1–10. As mentioned before, all monetary values are expressed in constant 2009 PLN and discounted using a 4% real discount rate.

Ownership costs include acquisition cost, insurance and taxes, and technical inspections. Residual value represents the discounted expected recovery value at the end of Year 10 and is therefore presented as a negative cost. Acquisition cost is shown separately for information only and is already included within ownership costs.

5.3.1 Ownership-Cost Results

The ownership-cost result reflects the capital consumed during the holding period, in this considered as 10 years. Machines with high acquisition prices and low residual values generate a larger ownership-cost burden. Conversely, equipment retaining a high proportion of its initial value may present a lower net ownership cost even when its purchase price is high.

The following tables present ownership costs by equipment family, expressed per unit of utilisation and as a ten-year average annual expenditure. For heavy equipment, ownership costs are normalised by operating hours; for trucks, they are normalised by kilometres travelled. The annual column facilitates comparison between equipment families whose utilisation differs substantially.

Table 6: Ownership Costs (Heavy Equipment)

Equipment family	Total working time, h	Depreciation, PLN/h	Insurance, PLN/h	Total ownership cost, PLN/h	Average annual ownership cost, PLN/year
Asphalt paver	17,066	3.740	0.903	4.643	7,923
Backhoe loader	113,561	1.849	0.377	2.226	25,279
Bulldozer	49,488	3.543	0.859	4.402	21,786
Crawler excavator	101,014	3.447	0.811	4.258	43,013
Motor grader	73,217	1.760	0.458	2.218	16,242
Pneumatic tyre roller	48,679	1.711	0.446	2.157	10,499
Single-drum soil compactor	102,971	1.875	0.490	2.365	24,355

Equipment family	Total working time, h	Depreciation, PLN/h	Insurance, PLN/h	Total ownership cost, PLN/h	Average annual ownership cost, PLN/year
Tandem drum compactor	19,086	1.741	0.441	2.182	4,164
Wheeled excavator	33,344	3.733	0.920	4.653	15,515
Wheel loader	76,002	4.120	0.954	5.074	38,565

Table 7: Ownership Costs (Trucks)

Equipment family	Total mileage, km	Depreciation, PLN/km	Insurance, PLN/km	Total ownership cost, PLN/km	Average annual ownership cost, PLN/year
Hauling truck	6,069,926	0.0494	0.0067	0.0561	34,029
Tipper truck	4,014,699	0.0537	0.0090	0.0627	25,158
Asphalt sprayer	446,111	0.0369	0.0056	0.0425	1,895

Wheel loaders record the highest ownership cost per operating hour, at 5.07 PLN/h, followed by wheeled excavators, asphalt pavers, bulldozers and crawler excavators. Backhoe loaders, motor graders, pneumatic tyre rollers and compactors show lower hourly ownership costs. Among trucks, tipper trucks have the highest ownership cost per kilometre, at 0.0627 PLN/km, followed by hauling trucks and asphalt sprayers.

The average annual ownership-cost column shows a different pattern from the hourly and per-kilometre indicators because it reflects both unit costs and the scale of utilisation. Crawler excavators

and wheel loaders have the highest annual ownership expenditure among heavy-equipment families, while hauling trucks have the highest annual ownership expenditure among trucks. This distinction is important: a family may have a high cost per hour or kilometre but a lower total financial exposure if its utilisation is limited.

This indicator can be misleading and should only be compared with machines that present similar tasks and workloads. A high ownership cost per hour typically reflects lower utilization rather than poor management by itself.

5.3.2 Maintenance-Cost Results

Preventive-maintenance cost per hour is obtained by dividing the total preventive maintenance cost spent on each category by the total working hours performed. Corrective-maintenance and repair costs per hour were obtained in a similar way to preventive maintenance hourly costs, by dividing the total corrective maintenance cost spent on each category by the total working hours performed.

The following tables present preventive, corrective and total maintenance expenditure normalised by equipment utilisation. Heavy-equipment results are expressed per operating hour, while truck results are expressed per kilometre. Each ratio was calculated by dividing the family's discounted maintenance expenditure over the ten-year period by its corresponding cumulative utilisation. The separation of preventive and corrective expenditure shows their respective contributions to total maintenance costs.

Table 8: Table 15: Total Maintenance Costs per hour (heavy equipment)

Equipment family	Total working time, h	Preventive maintenance, PLN/h	Corrective maintenance, PLN/h	Total maintenance, PLN/h
Asphalt paver	17,066	4.643	3.239	7.882
Backhoe loader	113,561	2.226	0.597	2.823
Bulldozer	49,488	4.402	1.977	6.379

Equipment family	Total working time, h	Preventive maintenance, PLN/h	Corrective maintenance, PLN/h	Total maintenance, PLN/h
Crawler excavator	101,014	4.258	2.451	6.710
Motor grader	73,217	2.218	1.092	3.311
Pneumatic tyre roller	48,679	2.157	0.745	2.902
Single-drum soil compactor	102,971	2.365	1.273	3.638
Tandem drum compactor	19,086	2.182	1.060	3.242
Wheeled excavator	33,344	4.653	1.878	6.531
Wheel loader	76,002	5.074	1.938	7.012
Fleet total / weighted ratio	634,428	3.268	1.491	4.759

Table 9; Total Maintenance Costs per Km (Trucks)

Equipment family	Total mileage, km	Preventive maintenance, PLN/km	Corrective maintenance, PLN/km	Total maintenance, PLN/km
Hauling truck	6,069,926	0.0561	0.0645	0.1206
Tipper truck	4,014,699	0.0627	0.1675	0.2301
Asphalt sprayer	446,111	0.0425	0.0904	0.1328
Fleet total / weighted ratio	10,530,736	0.0580	0.1049	0.1629

Tracking maintenance cost per operating hour normalizes expenditure across equipment with different utilization levels; separating planned/preventive from corrective work is also useful for evaluating maintenance control and replacement decision.

Among heavy-equipment families, wheel loaders record the highest total maintenance cost per operating hour, at 7.01 PLN/h, followed by asphalt pavers, crawler excavators, wheeled excavators and bulldozers. Backhoe loaders have the lowest hourly maintenance cost, at 2.82 PLN/h. Preventive maintenance accounts for the majority of maintenance expenditure in all heavy-equipment families, ranging from 58.9% for asphalt pavers to 78.9% for backhoe loaders.

Among trucks, tipper trucks have the highest total maintenance cost per kilometre, at 0.2301 PLN/km, followed by asphalt sprayers and hauling trucks. In contrast to heavy equipment, corrective maintenance represents the larger share of maintenance expenditure for all truck families. This is particularly pronounced for tipper trucks, where corrective maintenance accounts for 72.8% of total maintenance costs, suggesting greater exposure to unplanned repairs and potentially higher downtime risk.

In road-construction activities, the backhoe loader may remain available for intermittent tasks such as culvert lifting, pipe handling, minor excavation, loading, or support work. Although the machine

may not be continuously moving or actively producing output, it is kept ready for immediate use and continues to accumulate recorded operating hours.

5.3.3 Fuel Costs

The following tables present the fuel consumption and fuel costs by equipment family. Consumption is normalised by operating hours for heavy equipment and by kilometres for trucks, allowing comparison of fuel intensity across equipment types. The table also reports the ten-year average annual fuel consumption and expenditure, which reflects both fuel intensity and the scale of each family's utilisation.

Table 10: Fuel consumption per hour (Heavy Equipment)

Equipment family	Total working time, h	Fuel consumption, L/h	Fuel cost, PLN/h	Fuel price, PLN/L	Average annual fuel consumption, L/year	Average annual fuel cost, PLN/year
Asphalt paver	17,066	4.972	7.324	1.473	8,485	12,500
Backhoe loader	113,561	4.593	6.867	1.495	52,153	77,982
Bulldozer	49,488	8.722	13.051	1.496	43,164	64,586
Crawler excavator	101,014	7.918	11.833	1.494	79,987	119,533
Motor grader	73,217	4.803	7.179	1.495	35,165	52,563

Equipment family	Total working time, h	Fuel consumption, L/h	Fuel cost, PLN/h	Fuel price, PLN/L	Average annual fuel consumption, L/year	Average annual fuel cost, PLN/year
Pneumatic tyre roller	48,679	3.873	5.790	1.495	18,855	28,183
Single-drum soil compactor	102,971	4.015	6.008	1.496	41,344	61,862
Tandem drum compactor	19,086	3.323	4.966	1.495	6,342	9,479
Wheeled excavator	33,344	5.349	8.000	1.496	17,836	26,674
Wheel loader	76,002	6.775	10.130	1.495	51,493	76,987

Table 11: Fuel consumption per Km (Trucks)

Equipment family	Total mileage, km	Fuel consumption, L/km	Fuel cost, PLN/km	Fuel price, PLN/L	Average annual fuel consumption, L/year	Average annual fuel cost, PLN/year
Hauling truck	6,069,926	0.321	0.482	1.504	194,531	292,514

Equipment family	Total mileage, km	Fuel consumption, L/km	Fuel cost, PLN/km	Fuel price, PLN/L	Average annual fuel consumption, L/year	Average annual fuel cost, PLN/year
Tipper truck	4,014,699	0.372	0.559	1.503	149,267	224,322
Asphalt sprayer	446,111	0.298	0.447	1.502	13,286	19,957

Note. Fuel consumption is calculated by dividing total fuel used over the ten-year analysis period by cumulative operating hours for heavy equipment or cumulative kilometres for trucks. Fuel cost is calculated analogously from discounted fuel expenditure. The average fuel price is derived as fuel expenditure divided by litres consumed and therefore represents the realised average price rather than an assumed price. Average annual values are ten-year totals divided by ten. Monetary values are in constant 2009 PLN, excluding VAT. Minor differences arise from rounding.

Among heavy-equipment families, bulldozers are the most fuel-intensive per operating hour, consuming 8.72 L/h, followed by crawler excavators at 7.92 L/h and wheel loaders at 6.78 L/h. Tandem drum compactors and pneumatic tyre rollers have the lowest fuel consumption per hour. These differences reflect engine power, machine weight, working cycle and the nature of the tasks performed. This does not necessarily mean that the wheel loader or bulldozer have inefficient operation. Larger machines performing high-load tasks naturally consume more fuel per hour. The metric becomes most useful when comparing similar machines, the same machine over time, different operators, or fuel cost per unit of output—for example PLN/m³ moved, PLN by ton placed, or PLN/km hauled.

Among trucks, tipper trucks have the highest fuel consumption and cost per kilometre, at 0.372 L/km and 0.559 PLN/km respectively. Hauling trucks and asphalt sprayers show lower per-kilometre fuel intensity. However, hauling trucks have the highest average annual fuel expenditure because of their substantially higher annual mileage. This illustrates that per-unit fuel intensity and total financial exposure must be assessed separately.

5.3.4 Tyre, and Track Costs

Tyre and track costs per hour can be useful indicator for equipment categories in which undercarriage and tyre wear represent a significant operating-cost component. The indicator is especially relevant for crawler excavators and bulldozers.

By relating tyre, track, and undercarriage expenditure to recorded operating hours, it enables the comparison of wear-related costs between equipment categories and supports maintenance, replacement, and procurement decisions.

The following tables present tyre and track costs by equipment family, normalised by operating hours for heavy equipment and kilometres for trucks. The annual expenditure column additionally reflects the utilisation intensity of each family. For tracked machines, the reported expenditure represents track-related wear and replacement costs; for wheeled machines, it represents tyre-related costs.

Table 12: Tyre or track costs per hour (Heavy Equipment)

Equipment family	Total working time, h	Tyre or track cost, PLN/h	Average annual tyre or track cost, PLN/year
Asphalt paver	17,066	1.376	2,349
Backhoe loader	113,561	0.675	7,668
Bulldozer	49,488	1.666	8,247
Crawler excavator	101,014	1.450	14,643
Motor grader	73,217	0.772	5,654
Pneumatic tyre roller	48,679	0.566	2,754
Single-drum soil compactor	102,971	0.629	6,480

Equipment family	Total working time, h	Tyre or track cost, PLN/h	Average annual tyre or track cost, PLN/year
Tandem drum compactor	19,086	0.470	896
Wheeled excavator	33,344	1.217	4,059
Wheel loader	76,002	1.431	10,874

Table 13: Tyre Cost per Km (Trucks)

Equipment family	Total mileage, km	Tyre cost, PLN/km	Average annual tyre cost, PLN/year
Hauling truck	6,069,926	0.0236	14,354
Tipper truck	4,014,699	0.0271	10,880
Asphalt sprayer	446,111	0.0139	622

Note. Tyre or track cost is calculated by dividing each family's ten-year discounted tyre/track expenditure by cumulative operating hours for heavy equipment or cumulative kilometres for trucks. The annual column divides the ten-year expenditure by ten. For tracked machines, the expenditure represents track-related wear and replacement; for wheeled machines, it represents tyre-related costs. Monetary values are in constant 2009 PLN, excluding VAT. Minor differences arise from rounding.

Among heavy-equipment families, bulldozers record the highest tyre or track cost per operating hour, at 1.67 PLN/h, followed by wheel loaders, crawler excavators, asphalt pavers and wheeled excavators. Tandem drum compactors and pneumatic tyre rollers show the lowest hourly costs. The high hourly cost for bulldozers is consistent with the greater wear intensity associated with tracked equipment and demanding earthmoving operations.

Among trucks, tipper trucks have the highest tyre cost per kilometre, at 0.0271 PLN/km, followed by hauling trucks and asphalt sprayers. However, hauling trucks have the highest average annual tyre expenditure because of their higher annual mileage. As with fuel costs, the per-kilometre indicator reflects wear intensity, whereas the annual cost indicator reflects the overall financial exposure of each family.

5.4 Total LCC by Equipment Category

The total LCC for each category was obtained by aggregating the individual asset results. Since the number of units differs considerably between categories, both total and average values should be presented.

Table 14:Ten-year discounted life-cycle costs by equipment family

	Units	WORKING TIME	ACQUISITION COSTS	OWNERSHIP COSTS	MAINTENANCE COSTS	TYRES TRACKS	FUEL	RESIDUAL VALUE	LCC Per Family
		hours	PLN	PLN	PLN	PLN	PLN	PLN	PLN
Asphalt paver	2	**17,066**	**2,248,347**	**182,095**	**134,515**	**169,595**	**562,247**	**-424,159**	**2,872,641**
Backhoe loader	7	**113,561**	**1,348,243**	**595,067**	**320,569**	**459,094**	**1,985,751**	**-189,520**	**4,519,204**
Buldozer	3	**49,487**	**2,327,984**	**273,142**	**315,694**	**467,671**	**1,597,054**	**-467,528**	**4,514,018**
Crawler excavator	6	**101,015**	**3,307,327**	**522,133**	**677,753**	**1,001,562**	**2,996,532**	**-664,889**	**7,840,418**
Motorgrader	6	**73,218**	**5,177,409**	**534,209**	**242,401**	**287,328**	**1,623,017**	**-1,076,735**	**6,787,630**
Pneumatic tyre roller	4	**48,679**	**1,079,401**	**352,114**	**141,249**	**150,782**	**876,541**	**-216,021**	**2,384,066**
Single Drum Compactor	7	**102,972**	**2,317,962**	**607,143**	**374,607**	**159,176**	**1,889,460**	**-471,182**	**4,877,166**
Tandem Drum Compactor	2	**19,085**	**620,786**	**170,019**	**61,884**	**29,919**	**399,945**	**-108,216**	**1,174,337**
Wheel excavator	2	**33,344**	**1,943,423**	**170,019**	**217,755**	**89,718**	**960,655**	**-338,781**	**3,042,789**
Wheel loader	6	**76,002**	**5,688,147**	**516,096**	**532,926**	**381,712**	**2,163,245**	**-1,136,510**	**8,145,615**
		TOTAL:	**26,059,029**	**3,922,038**	**3,019,353**	**3,196,558**	**15,054,446**	**-5,093,541**	**46,157,883**

Table 15: Ten-year discounted life-cycle costs by truck family

	Units	MILEAGE	ACQUISITION COSTS	OWNERSHIP COSTS	MAINTENANCE COSTS	TYRES TRACKS	FUEL	RESIDUAL VALUE	LCC Per Family
		Km	PLN	PLN	PLN	PLN	PLN	PLN	PLN
Hauling truck	16	6,069,926	4,596,110	1,395,896	731,880	391,547	4,055,507	-659,553	10,511,387
Tipper truck	21	4,014,699	11,083,754	1,752,231	923,912	741,613	3,019,372	-1,497,557	16,023,326
Asphalt Sprayer	2	446,111	983,032	182,095	59,260	39,935	318,040	-149,544	1,432,819
		TOTAL:	**16,662,897**	**3,330,222**	**1,715,051**	**1,173,096**	**7,392,919**	**-2,306,654**	**27,967,531**

5.5 Deterministic Economic Replacement Age

For each equipment unit, EUAC was calculated for successive possible holding periods. The deterministic economic replacement age was defined as the age at which EUAC reached its minimum:

$$n^* = \arg \min_{n \in \{1,2,\ldots,N\}} EUAC(n)$$

This recommended replacement age is therefore represented by n^* that is the cost-minimizing holding period under the assumptions adopted in the model.

A machine whose current age is greater than $n^*$is operating beyond the deterministic economic replacement age according to the model. A machine whose current age is lower than n^*has not yet reached the calculated replacement point, provided that its operating condition and required service capacity remain acceptable.

The following table summarises the deterministic economic replacement age obtained from the EUAC analysis. For each equipment family, it reports the number of units analysed, the current age range, the range of indicated replacement years, and the number of machines that have already reached or exceeded their indicated replacement age. The underlying EUAC calculations for each individual machine are presented in Appendix Table A1.

Table 19: Summary of indicated replacement years by equipment family

Equipment family	Units analysed	Earliest indicated replacement year	Latest indicated replacement year	Distribution of indicated replacement years
Asphalt paver	2	2007	2009	**2007: 1; 2009: 1**
Backhoe loader	7	2017	2017	**2017: 7**
Bulldozer	3	2006	2008	**2006: 2; 2008: 1**
Crawler excavator	6	2008	2017	**2008: 2; 2009: 1; 2010: 1; 2017: 2**

Equipment family	Units analysed	Earliest indicated replacement year	Latest indicated replacement year	Distribution of indicated replacement years
Milling machine	2	2000	2000	**2000: 2**
Motor grader	5	2007	2009	**2007: 1; 2008: 2; 2009: 2**
Pneumatic tyre roller	4	2013	2017	**2013: 2; 2016: 1; 2017: 1**
Single-drum compactor	7	2009	2017	**2009: 1; 2010: 2; 2016: 3; 2017: 1**
Tandem drum compactor	2	2017	2017	**2017: 2**
Wheeled excavator	2	2016	2016	**2016: 2**
Wheel loader	6	2006	2010	**2006: 1; 2009: 1; 2010: 4**
Total	**46**	**2000**	**2017**	**—**

Table 16: Summary of indicated replacement years by truck family

Equipment family	Units analysed	Earliest indicated replacement year	Latest indicated replacement year	Distribution of indicated replacement years
Hauling truck	16	2012	2018	**2012: 5; 2014: 3; 2018: 8**
Tipper truck	21	2016	2018	**2016: 2; 2018: 19**
Asphalt sprayer	2	2007	2007	**2007: 2**
Total	**39**	**2007**	**2018**	—

The EUAC results identify the age at which the annualised cost of retaining each machine is minimised. The range of indicated replacement years within each family reflects differences in acquisition year, utilisation, maintenance history, residual value and operating conditions. Therefore, the results should be interpreted at machine level rather than as a single replacement age for an entire equipment family.

Machines whose current age is equal to or greater than the indicated replacement age should be prioritised for replacement review. However, a replacement recommendation should not be based solely on the minimum-EUAC result. Technical condition, expected downtime, overhaul history, availability requirements and capital constraints must also be considered before a final retain, repair, overhaul or replace decision is made.

5.6 Comparison with Current Replacement Practice

The LCC-based recommendation was compared with the company's current replacement practice. The comparison focused on whether the company replaced equipment before, near, or after the age indicated by the minimum EUAC.

The comparison should distinguish between three situations:

- **LCC recommends earlier replacement:** the machine is being retained beyond the calculated minimum-EUAC point.
- **LCC recommends later replacement:** empirical replacement occurs before the calculated minimum-EUAC point.
- **Similar replacement timing:** empirical and LCC-based decisions are broadly aligned.

  The economic benefit of the LCC approach should be quantified using:

$$\Delta LCC = LCC_{\text{empirical}} - LCC_{\text{LCC-based}}$$

A positive value indicates a reduction in cost under the LCC-based policy. The relative reduction is:

$$\text{Reduction (\%)} = \frac{LCC_{\text{empirical}} - LCC_{\text{LCC-based}}}{LCC_{\text{empirical}}} \times 100$$

These calculations are required before H1 can be accepted. If the comparison is available only for selected machines or categories, H1 should be assessed as partially supported rather than generalized to the entire fleet.

5.7 Cost Evolution with Age and Operating Hours

The relationship between cost and equipment age was analyzed using annual maintenance cost, maintenance cost per operating hour, total LCC per hour, and EUAC. The analysis distinguishes between calendar age and operating exposure because machines with the same age may have substantially different accumulated operating hours.

The following indicators were calculated:

$$C_{\text{maint/hour},j} = \frac{C_{PM,j} + C_{CM,j}}{H_j}$$

$$C_{\text{LCC/hour},j} = \frac{LCC_j}{H_j}$$

The results should be presented using:

- maintenance cost per hour versus cumulative operating hours;
- total LCC per hour versus equipment age;
- EUAC versus replacement age;
- preventive and corrective maintenance as separate cost series;
- major repair events identified on the same time axis.

Particular attention should be given to motor graders, crawler excavators, bulldozers, wheel loaders, and high-utilization trucks because these categories may show stronger relationships between accumulated use, major repair events, and economic replacement timing. However, the conclusion that maintenance costs increase with age or operating hours must be based on the calculated results rather than assumed from equipment type.

5.7.1 Stochastic LCC model (Monte Carlo simulation)

Monte Carlo simulation replaces uncertain single-value inputs with probability distributions. The model repeatedly samples from those distributions, calculates LCC for each iteration, and converts the resulting outcomes into a cost distribution. The practical design choices are: which inputs are uncertain, what distributions represent them, how many iterations to run, and what decision will be taken from the result.(*NIST, website consulted in June 2026*)

The stochastic simulations are useful to assess a practical risk range, not just a single LCC estimate. The percentile P50, or median, can be used as baseline planning, while a contingency can be stipulated for adverse fuel and residual-value outcomes, and a higher contingency can be applied

more actively to heavy equipment because its absolute uncertainty is much larger (*Risk Publishing, Website consulted in June 2026*)

The deterministic LCC model was expressed in constant 2009 PLN and discounted using a real discount rate of 4%. The 10-year discounted LCC was estimated at PLN 55.853 million for heavy equipment and PLN 28.332 million for trucks. The Monte Carlo model was calibrated so that its central input values reproduced the deterministic estimates.

For this case study, it is assumed that uncertainty is represented by fuel-price and residual-value multipliers, while the 4% real discount rate was retained as the base-case rate. This option ensures that deviations in simulated LCC are attributable to the stochastic variables rather than to unforeseen variations in cash flows or residual values.

A Monte Carlo simulation with 10,000 iterations was conducted to evaluate uncertainty in the 10-year discounted life-cycle cost of the fleet [see attached Excel workbook].

As usual, all monetary values are expressed in constant 2009 PLN.

The stochastic model was calibrated so that the central values of the uncertain inputs reproduced the deterministic LCC estimates. Fuel-cost and residual-value uncertainty were represented by triangular distributions centred on their deterministic values.

When we refer to the variables “fuel price” or “residual value,” we are not actually referring to the variables themselves but to their variation. That is why, when choosing the parameters for the continuous triangular distribution, the central value is 1, while the intervals are defined by a variation of $-20\%$to $+20\%$in the case of the fuel-price multiplier and $-30\%$to $+30\%$in the case of the residual-value multiplier.

For heavy equipment, the deterministic LCC was PLN 5546,853,319.

After running the simulation, the mean simulated LCC was PLN 55,853,325, differing by only PLN 6 from the deterministic value. The median LCC was PLN 55,820,550.

The P10 and P90 values were PLN 52,885,696 and PLN 58,817,062, respectively, while the minimum and maximum simulated outcomes were PLN 49,894,405 and PLN 61,712,335. The standard deviation was PLN 2,198,430. The probability of the simulated LCC exceeding the deterministic value was 49.47%.

For trucks, the deterministic LCC was PLN 28,232,978.

After running the simulation, the mean simulated LCC was PLN 28,232,980. The median was PLN 28,224,658.

The P10 and P90 values were PLN 27,164,324 and PLN 29,298,672, respectively. The simulation generated a minimum result of PLN 25,990,193 and a maximum result of PLN 30,409,851, with a standard deviation of PLN 793,969. The probability of exceeding the deterministic LCC was 49.68%.

As can be observed, the deterministic LCC value and the mean simulated value are not very far apart, which means that the parameters chosen for the triangular distributions were consistent.

Table 17: Stochastic simulation results

	Heavy Equipment (constant 2009 PLN)	Trucks (constant 2009 PLN)
P10	52,885,696 PLN	27,164,324 PLN
P50	55,820,550 PLN	28,224,658 PLN
P90	58,817,062 PLN	29,298,672 PLN

For heavy equipment, the 10th percentile means that there is a 10% probability that the discounted LCC could be below PLN 52,885,696. The difference between P10 and P90 is approximately PLN 5.93 million, indicating the range of LCC uncertainty generated by the stochastic fuel-cost and residual-value assumptions.

For trucks, the central 80% simulation interval ranged from PLN 27,164,324 to PLN 29,298,672, representing an uncertainty range of almost PLN 2.13 million around the median estimate.

Heavy equipment exhibited materially higher absolute uncertainty than trucks, with a P90–P50 difference of approximately PLN 3.00 million, compared with approximately PLN 1.07 million for trucks. Accordingly, the P50 LCC may be adopted as a central planning estimate, while the P90

value provides a more conservative basis for budgeting, tender pricing, and fleet-management decisions presented.

5.8 SPECIAL CASES IN REPLACEMENT STRATEGY

Let's organize all possible cases into two groups according to one specific rule: the need of extra analysis beyond EUAC minimum determination.

5.8.1 Cases identified solely through EUAC analysis:

The evolution of the equivalent uniform annual cost (EUAC) curve provides an initial basis for identifying economically attractive retention periods and results requiring further validation. Ten diagnostic cases were defined, covering clear minima, first-year minima, incomplete cost histories, flat curves, boundary minima, continuously increasing or declining costs, irregular profiles, multiple minima, and exceptional cost events.

These cases are identified initially through the EUAC results, although their causes may require examination of the underlying records and assumptions. The minimum EUAC identifies the cost-minimising retention period under the adopted assumptions; it does not, by itself, establish that an existing machine should be replaced immediately. That decision may require comparison between continued retention of the existing machine—the defender—and a replacement alternative—the challenger.sfu+1

Table 18: Replacement Strategy. Cases only depending on EUAC

Case	EUAC pattern	Brief description
1.1	Normal EUAC minimum	A clear minimum identifies the economically optimal replacement age.
1.2	Minimum in Year 1	The lowest EUAC occurs immediately, suggesting a possible early-replacement signal.
1.3	Incomplete early costs	Missing early-year costs may create an artificially low initial EUAC.

Case	EUAC pattern	Brief description
1.4	Flat EUAC curve	Similar EUAC values indicate several economically comparable replacement dates.
1.5	Minimum at final year	The minimum occurs at the end of the horizon, suggesting a longer analysis period may be needed.
1.6	EUAC increases from Year 1	Continuously rising EUAC indicates that the asset may already be beyond its economic life.
1.7	Irregular EUAC curve	Sudden changes suggest possible errors in costs, residual values, or cash flows.
1.8	Non-unique or flat minimum	Several ages have similar EUAC values, supporting a replacement window rather than one exact year.
1.9	Horizon-limited EUAC result	EUAC continues to fall, meaning the true economic life may lie beyond the analysed period.
1.10	Abnormal cost event	One exceptional cost or data entry may distort the EUAC result and requires validation.

Note. *Author-developed diagnostic framework informed by the equipment life-cycle cost and economic-life principles discussed by Gransberg and O'Connor (2015). The ten-case classification and illustrative scenarios were developed specifically for this study and are not reproduced from that publication.*

Illustrative calculations and graphs for each case are presented in Appendix X, using a common machine template with selected cash-flow modifications. These illustrations are distinguished from actual fleet results. Where a corresponding pattern is identified among the 91 machines, the relevant equipment unit is referenced separately.

Case 1.1) Normal EUAC minimum

Abundantly covered on our fleet's case study. The replacement year will be the one with the lowest EUAC as the economically optimal replacement age, provided that the result is supported by complete and reliable cost data. The EUAC curve decreases, reaches a distinct minimum within the analysed period, and subsequently increases. This pattern reflects the balance between capital-related costs and operating and maintenance expenditure over the equipment's service life. The minimum identifies the cost-minimising retention age under the adopted assumptions, provided that the cost inputs and residual-value estimates are sufficiently reliable (Gransberg & O'Connor, 2015)

The illustrative calculation and curve are presented in Appendix X, Case 1.1. Where this pattern is identified in the actual fleet results, the corresponding equipment unit is referenced separately.

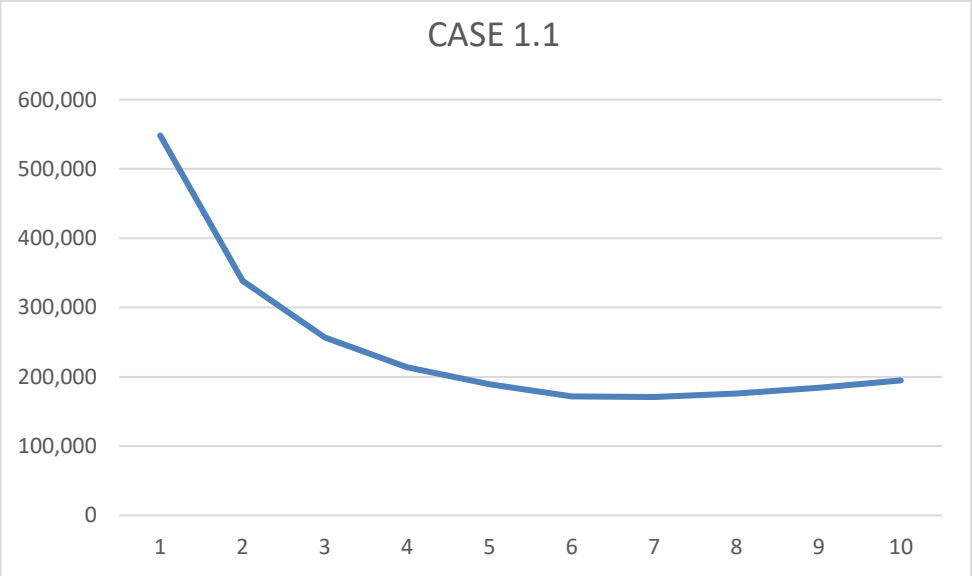


Figure 6: EUACcurve analysis - Case 1.1

Case 1.2) Minimum EUAC in Year 1

The lowest EUAC occurs in the first analysed year. Before interpreting this result, the acquisition cost, residual values, annual expenditure, discounting and definition of Year 1 should be verified. In particular, a first-year minimum in a historical analysis beginning at acquisition does not automatically justify replacing the machine today. A forward-looking comparison between the cost of continued retention and the cost of a challenger may still favour retaining the existing asset (Jones, 2008). If minimum occurs right on the first year the replacement may be economically preferable immediately. However, before taking an extreme decision it is convenient to verify the acquisition

cost, residual value, condition of the current asset, and whether the model includes all early ownership and operating costs or if some other inconsistency might have happen.

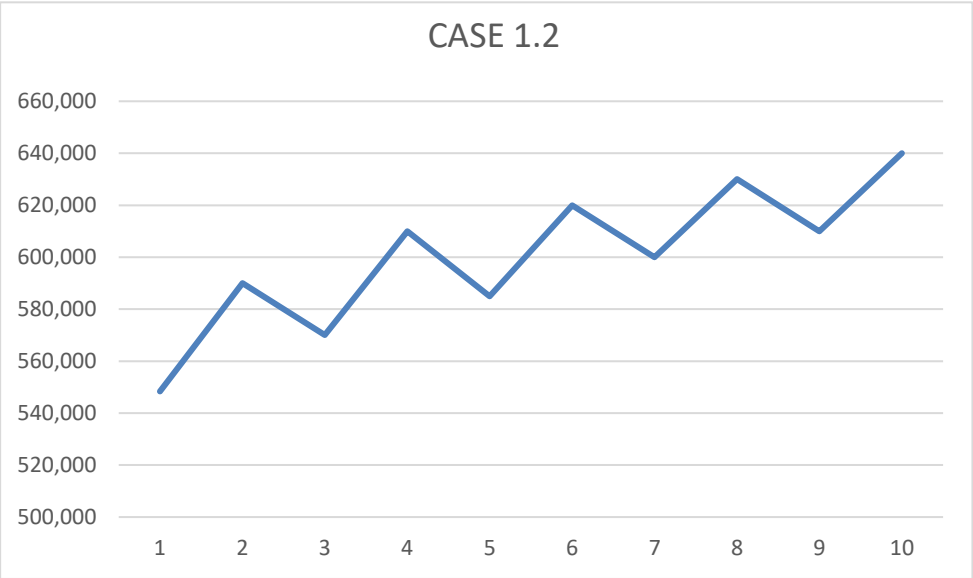


Figure 7: EUACcurve analysis - Case 1.2

Case 1.3) Incomplete early costs

The acquisition value is known, but operating and maintenance records for the first years are incomplete or unavailable. Treating missing expenditure as zero understates early cash flows and may produce a misleading early minimum. Missing values should therefore be identified explicitly, and any reconstruction or estimation should be documented and assessed for its influence on the result. This follows established cost-estimation principles concerning data validation, assumption documentation and sensitivity analysis (U.S. Government Accountability Office [GAO], 2020).

This can happen when the initial acquisition value of those machines is known but little or no records from their first operational years are available. The lack of information on operation costs created abnormally low cost cashflows on first years and triggering early replace signals

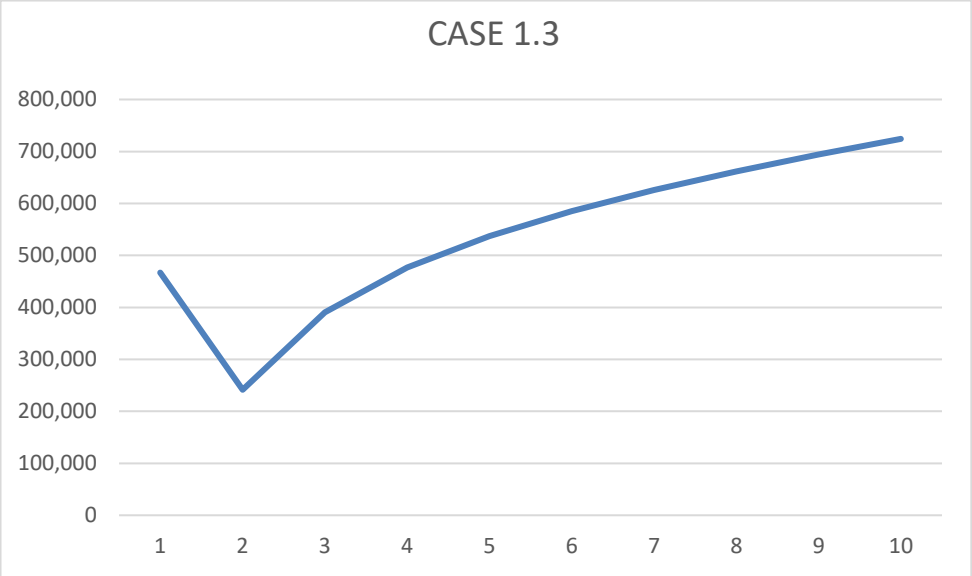


Figure 8: EUACcurve analysis - Case 1.3

Case 1.4): Flat EUAC curve

EUAC remains approximately constant across consecutive retention ages. Within this framework, the small differences indicate a replacement window rather than one economically decisive year. Operational considerations can subsequently inform the choice of a date within that window.

Low utilisation may contribute to the underlying cost profile, but a flat curve alone does not establish inactivity as its cause. The case is classified according to the similarity of consecutive EUAC values. Sensitivity testing can then establish whether this similarity persists under alternative input assumptions, consistent with the consideration of input uncertainty in equipment LCCA (Gransberg & O'Connor, 2015).

The equipment costs are all well known throughout its lifetime but due to machine long periods of inactivity due to limited have little use and therefore trigger replace signals without much economic reason.

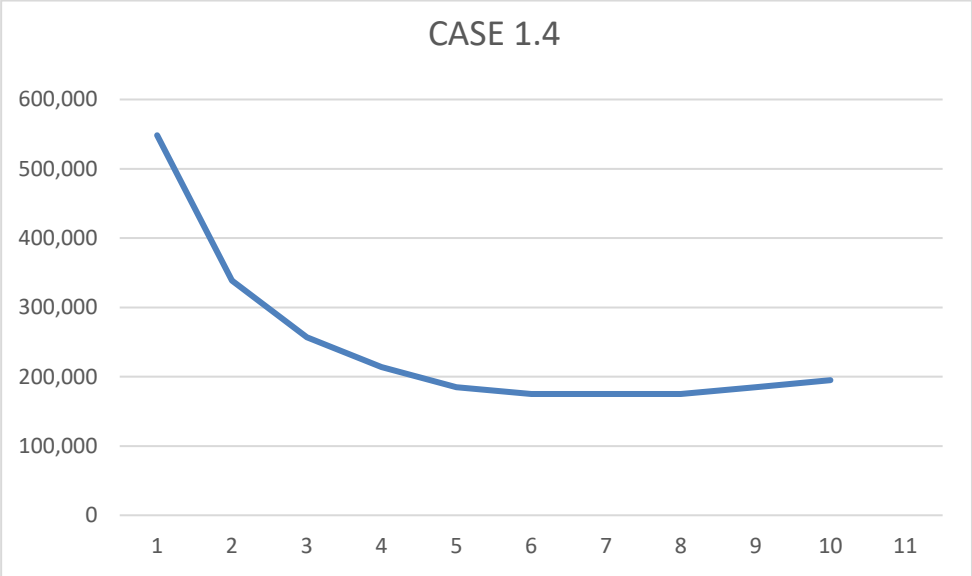


Figure 9: EUACcurve analysis - Case 1.4

Case 1.5) Minimum at final year

The lowest EUAC occurs in the final analysed year, following an otherwise fluctuating profile. In this study, this is classified as a boundary result: the final year is the cheapest retention period evaluated, but the calculation does not establish whether a lower value would occur later.

Where credible later-year cost and residual-value estimates are available, the analysis can be extended before treating the final year as a confirmed economic-life endpoint. Any extension should use documented assumptions rather than adjustments intended solely to produce a particular curve. The documentation and validation of estimated inputs are fundamental to reliable cost analysis (GAO, 2020).

If the lowest EUAC occurs in the final analyzed year, the true economic replacement age may be later. If possible, extending the analysis horizon to see how the EUAC curve develops before deciding if the asset should be retained until the final year.

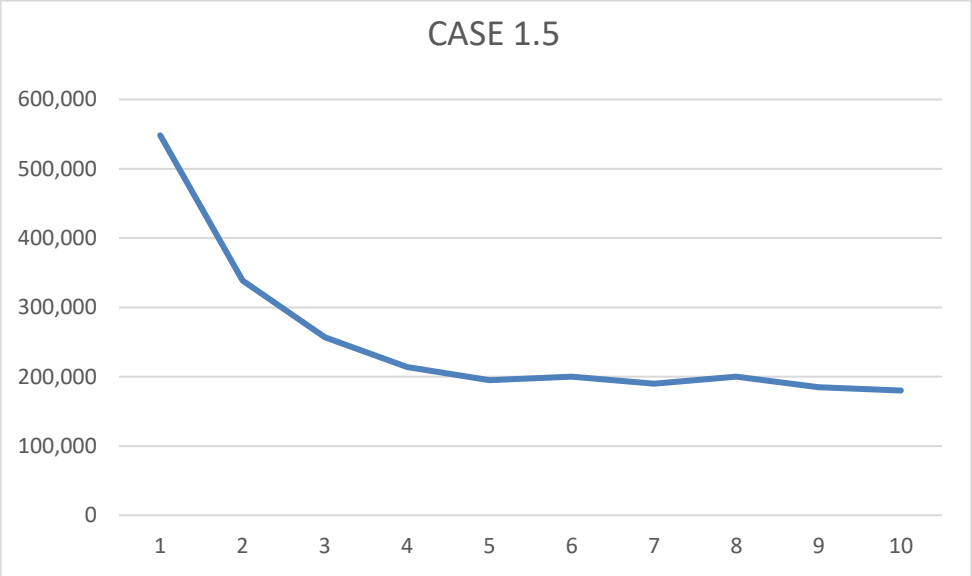


Figure 10: EUACcurve analysis - Case 1.5

Case 1.6) EUAC increases from Year 1

EUAC increases continuously from the first analysed year, making Year 1 the least-cost retention period within the evaluated range. However, this pattern alone does not prove that an existing asset is already beyond its economic life.

The starting point of the analysis, acquisition or current market value, cost escalation, residual values and annualisation should be checked. If the purpose is to decide whether to replace the machine now, a forward-looking defender–challenger comparison is required rather than relying solely on its historical EUAC curve (Jones, 2008).

A continuously increasing EUAC can indicate that the existing asset is already beyond its economic life. It can also indicate an error in residual value, acquisition cost, repair costs, discounting, or annualization.

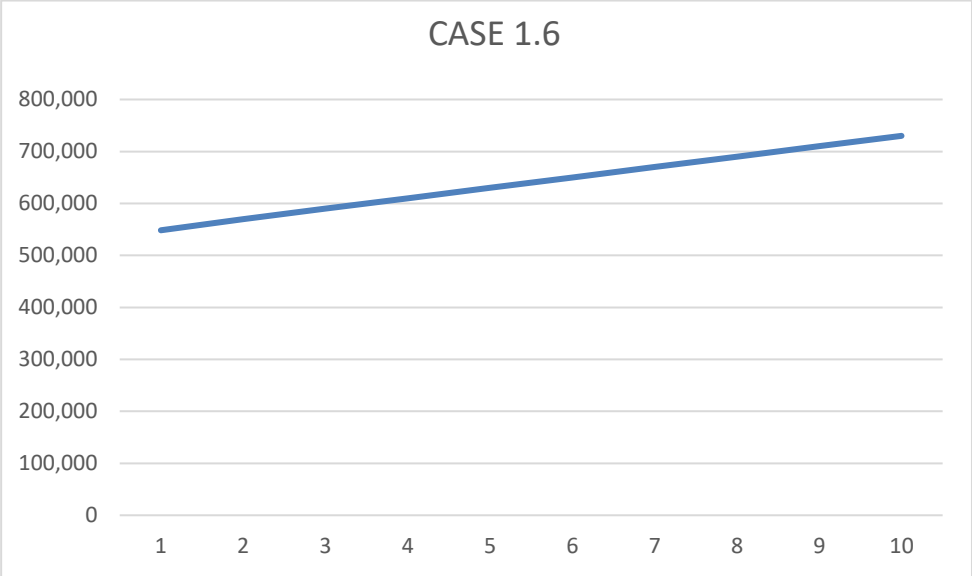


Figure 11; EUACcurve analysis - Case 1.6

Case 1.7) Irregular EUAC curve

Repeated peaks, drops or reversals require examination of the underlying cash flows. Potential explanations include genuine variations in utilisation and repair expenditure, incorrectly dated workshop orders, duplicate invoices, missing costs or inconsistent residual values. An irregular curve is therefore treated as a review signal, not as proof of an accounting or modelling error.

Sharp unexplained peaks or drops may indicate incorrect timing of cash flows, duplicate costs, missing repair records, inconsistent residual values, or data-entry errors. There might be abnormal repair logs, with misplaced dates on workshop orders, invoices, and accounting entries.

The review should verify the completeness, consistency and timing of the inputs and document any corrections. These procedures follow established cost-data validation principles (GAO, 2020).

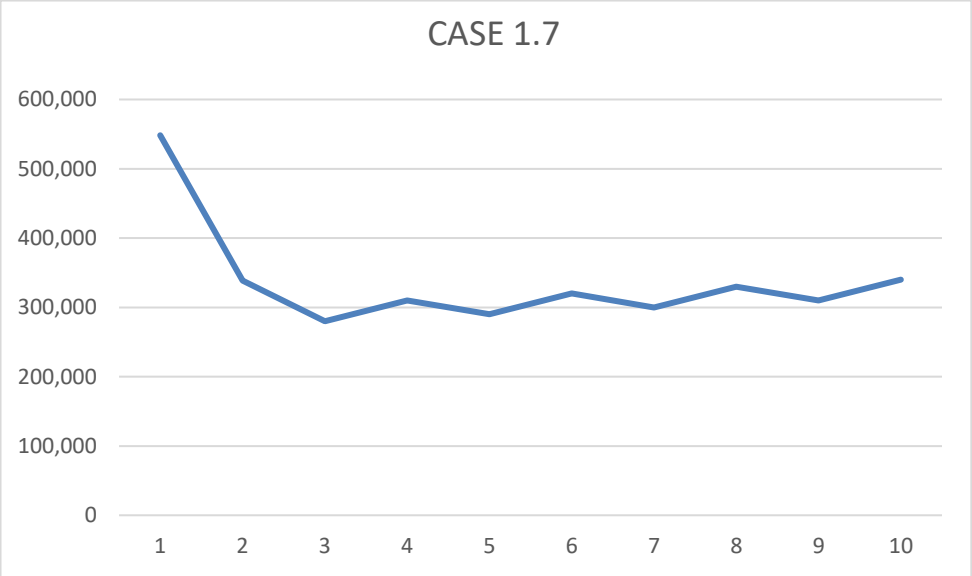


Figure 12: EUACcurve analysis - Case 1.7

Case 1.8) Non-unique minimum

Two or more separated retention ages produce equal or economically similar minimum EUAC values, with higher costs between them. Unlike the continuous flat region in Case 1.4, this pattern identifies distinct economic alternatives rather than one uninterrupted replacement window.

The alternatives should be examined in terms of their cost differences and sensitivity to the underlying assumptions. Sensitivity analysis is particularly relevant where small input changes could alter the preferred retention age, reflecting the importance of uncertainty in equipment economic-life assessment (Gransberg & O'Connor, 2015).

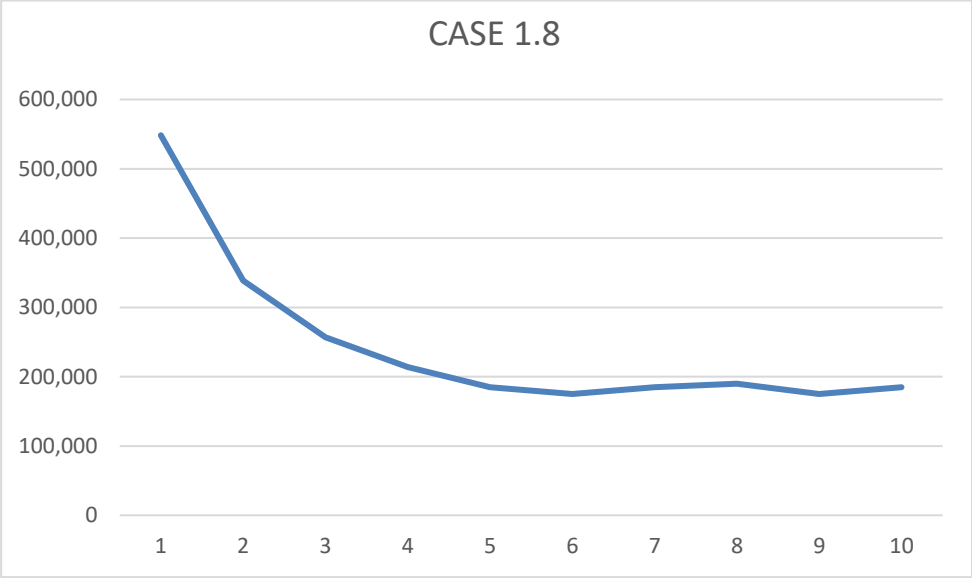


Figure 13: EUACcurve analysis - Case 1.8

Case 1.9) Horizon-limited EUAC result

EUAC decreases throughout the analysed period, so no internal minimum is identified. This differs from Case 1.5 because the decline is continuous rather than fluctuating. The result does not justify replacement in the final year or prove that EUAC will eventually rise. It indicates that the available data and assumptions have not identified a finite economic-life endpoint within the ten-year horizon.

The conventional economic-life calculation seeks the retention period with the lowest annual equivalent cost. Where that minimum has not been bounded within the evaluated period, the limitation should be reported rather than converted into an unsupported replacement recommendation (Jones, 2008).

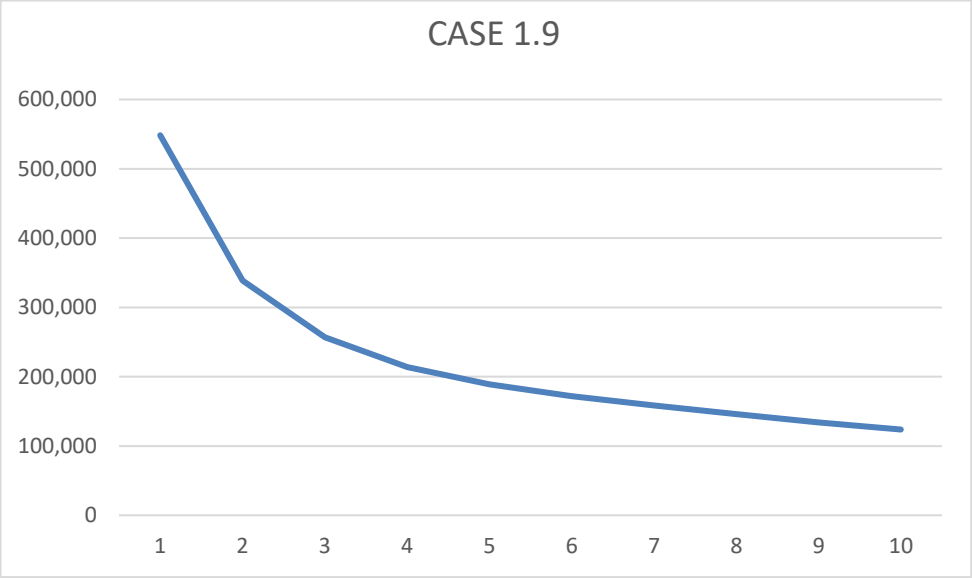


Figure 14: EUACcurve analysis - Case 1.9

Case 1.10) Abnormal cost event

A single exceptional event, such as a major repair, materially changes the EUAC curve. The event should first be checked for correct timing, classification and allocation. If genuine and within the defined historical cost scope, it should remain in the recorded dataset.

A separately labelled sensitivity comparison can then demonstrate how strongly the event influences the result without replacing the historical record. Varying the selected cost while holding the remaining assumptions constant follows established sensitivity-analysis principles (GAO, 2020).

Such testing is also consistent with the emphasis on input sensitivity in equipment life-cycle cost analysis (Gransberg & O'Connor, 2015)

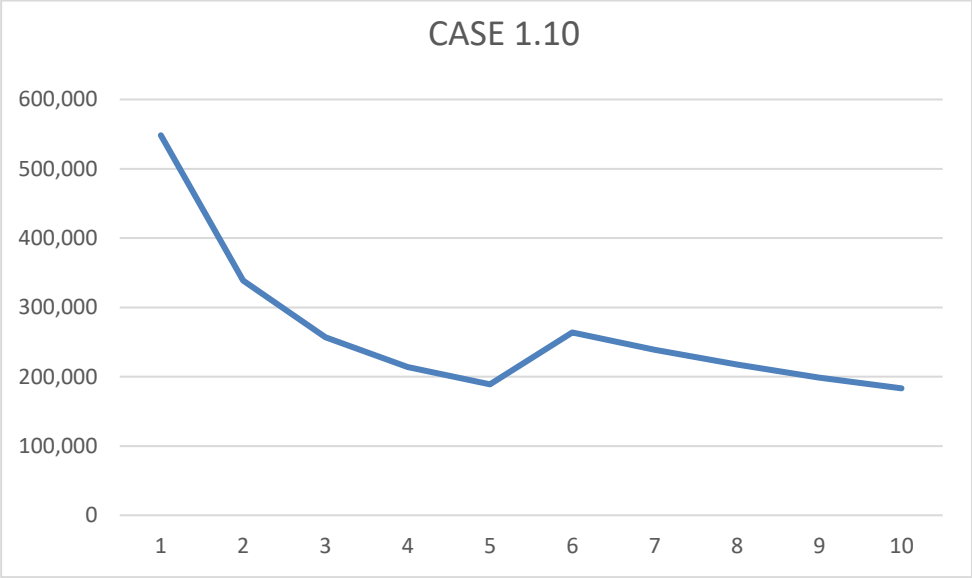


Figure 15: EUACcurve analysis - Case 1.10

The cases presented in Table 5.4 were selected to illustrate situations in which the reported EUAC-based replacement indication requires additional assessment before a final decision can be made. These cases involve differences in acquisition expenditure, results at the boundary of the evaluation period, variations in operating costs, early replacement indications, and the distinction between a truck chassis and its specialised installation. The proposed assessments complement the economic analysis by identifying the information needed to support an **evidence-based** replacement decision. They represent further verification requirements rather than completed assessments.

Machine ID / model	Reported replacement year	Additional evidence from the supplied results	Implication for interpretation	Recommendation
CE06 **Komatsu PC240 NLC-7, 2008**	2009	Acquisition cost is 235,485 PLN, compared with approximately 610,000 PLN for several other machines carrying the same model and	The different acquisition basis may affect the replacement result and comparability with the other excavators.	Verify purchase condition, model identification and acquisition value before adopting the replacement recommendation.

Machine ID / model	Reported replacement year	Additional evidence from the supplied results	Implication for interpretation	Recommendation
		commissioning year.		
BL01 **JCB 3CX, 2008**	2017	The indicated replacement year corresponds to the final evaluated year-column. The same result occurs for all seven backhoes.	The supplied result does not establish whether retaining the machine beyond the evaluated horizon would be preferable.	Extend the candidate replacement horizon before treating the reported year as a confirmed economic optimum.
BULL03 **Komatsu D65 EX, 2005**	2006	It has the highest displayed fuel and track expenditure among the three D65 machines, with broadly similar cumulative operating hours.	The operating-cost difference warrants investigation alongside the replacement indication.	Check fuel records, duty cycle and undercarriage replacement history; use a condition assessment to support the final retain/replace decision.
WL05 **Komatsu WA470-5, 2008**	2010	Acquisition expenditure is 999,747 PLN; the reported replacement year follows shortly after commissioning. WL06 has the same reported year.	The early replacement indication warrants checking the calculation and the practical consequences of replacement.	Verify the EUAC calculation, then compare retention with a documented replacement alternative before recommending disposal.
AS01 **Mercedes-Benz 2628 6×4**	2007	Its reported LCC includes both a truck chassis and a specialised	A whole-vehicle replacement decision may differ from a	Assess the chassis and spraying installation separately before

Machine ID / model	Reported replacement year	Additional evidence from the supplied results	Implication for interpretation	Recommendation
asphalt sprayer, 2005		installation; the supplied table does not separate their condition or remaining usefulness.	chassis-only or installation-only decision.	deciding whether to retain, refurbish or replace the complete unit.

5.8.2 Cases involving additional analysis:

Some replacement decisions require technical, operational, organisational or financial assessment in addition to EUAC analysis. In these situations, the lowest annual equivalent cost does not provide a sufficient basis for the final decision. Equipment management must also consider whether the asset remains suitable for its intended work and whether replacement, continued retention or refurbishment is practically feasible (Gransberg & O'Connor, 2015; Gransberg et al., 2006)

The fourteen cases presented in Table 36 form an author-developed framework for organising these additional considerations. They include safety and legal compliance, technological suitability, reliability, failure consequences, maintenance support, overhaul alternatives, procurement timing, fleet capacity, equipment interdependence, standardisation, investment constraints, market conditions, contractual requirements and tax effects.

These considerations may justify action before the minimum-EUAC retention age, delay an otherwise economically attractive replacement, or favour an alternative such as refurbishment, rental or reallocation. Where their effects can be estimated reliably, they should be incorporated into the economic comparison. Where they cannot be reduced adequately to monetary values, they should be documented separately as constraints or decision criteria. This distinction complements the broader repair–replace–retain approach of equipment life-cycle cost analysis (Gransberg & O'Connor, 2015).

Table 19: Replacement Strategy. Cases depending on additional analysis besides EUAC

Case	Event	Brief description
2.1	Safety and legal compliance	Continued operation depends on acceptable safety and compliance.
2.2	Technological suitability	New technology may better satisfy operational requirements.
2.3	Reliability and downtime	Breakdowns may generate losses beyond recorded repair costs.
2.4	Catastrophic-failure risk	Severe failure consequences may outweigh average-cost savings.
2.5	Parts and technical support	Limited support may compromise continued operation.
2.6	Major overhaul	Refurbishment may provide an alternative to replacement.
2.7	Replacement lead time	Procurement and delivery affect feasible replacement timing.
2.8	Fleet capacity	Replacement must preserve the capacity required for demand.
2.9	Equipment interdependence	An individual machine affects the performance of connected equipment.
2.10	Fleet standardisation	Replacement may offer benefits across the wider fleet.
2.11	Budget and financing	Investment constraints affect implementation of replacement decisions.

Case	Event	Brief description
2.12	Market conditions	Purchase prices and resale opportunities influence replacement economics.
2.13	Strategy and contracts	Equipment must satisfy future business and project requirements.
2.14	Tax and accounting effects	Relevant fiscal cash flows may alter the economic comparison.

Note. *Author-developed diagnostic framework informed by the equipment life-cycle cost and economic-life principles discussed by Gransberg and O'Connor (2015). The fourteen-case classification was developed for this study and is not reproduced from either publication.*

The cases in Table 36 are complementary rather than mutually exclusive: one machine may require assessment under several headings. The final recommendation should therefore distinguish:

- The economic signal produced by EUAC.
- Any technical, safety or compliance constraint.
- The operational and strategic implications.
- The feasibility of implementing the preferred alternative.

Case 2.1) Safety and legal compliance

Continued retention must first be assessed against applicable safety and legal requirements. Where a deficiency is identified, the alternatives may include repair, modification, restricted operation, withdrawal from service or replacement. A favourable EUAC result should not be interpreted as permission to continue operating an unsafe or non-compliant machine.

For this case study, the assessment should identify the relevant requirement, the equipment's compliance status and the feasibility of corrective action. Specific legal conclusions require reference to the regulations applicable to the machine and its operating location.

Case 2.2) Technological suitability

A replacement machine may offer capabilities that the existing asset cannot provide, such as improved control, productivity, compatibility or operating efficiency. The comparison should determine whether these capabilities are required and whether their benefits justify the investment, rather than treating newer technology as sufficient reason for replacement. Equipment selection, operating performance and economic replacement are related considerations within construction equipment management (Gransberg et al., 2006).

Case 2.3) Reliability and downtime

Recorded repair expenditure may not capture the full operational consequences of breakdowns. Additional effects can include idle personnel, replacement-equipment hire, interrupted production and project delays. Where supported by records, these consequences should be quantified and included in the comparison; otherwise, they should be reported as limitations or qualitative considerations.

Downtime should not be added twice if its monetary consequences are already included in the annual cash flows.

Case 2.4) Catastrophic-failure risk

This case concerns failures with potentially severe consequences rather than frequent routine breakdowns. The assessment should consider both the likelihood of failure and its possible consequences for personnel, equipment, the environment and project delivery.

A separate risk assessment may therefore be required alongside the average-cost comparison. The conclusion should identify whether continued operation is acceptable and whether inspection, preventive intervention or replacement is necessary.

Case 2.5) Parts and technical support

An asset may remain mechanically usable but become difficult to maintain because essential parts, specialist services or technical support are unavailable. The assessment should examine actual supplier availability, repair lead times, alternative components and maintenance capability.

Replacement should not be justified by age alone. The relevant issue is whether the machine can continue to receive dependable support within the company’s operational requirements.

Case 2.6) Major overhaul

A major overhaul should be evaluated as an alternative to both continued operation without intervention and replacement. The comparison should include the overhaul expenditure, associated downtime, expected subsequent operating costs, remaining service life and residual value.

This treatment is consistent with evaluating repair, replacement and retention alternatives through equipment life-cycle cost analysis (Gransberg & O'Connor, 2015).

Case 2.7) Replacement lead time

The economically preferred replacement date may differ from the date on which a suitable replacement can actually enter service. Procurement, manufacture, delivery, commissioning and operator preparation should therefore be considered when planning the transition.

The assessment should distinguish the date for initiating procurement from the date for withdrawing the existing machine. Temporary retention or rental may be required to bridge the interval.

Case 2.8) Fleet capacity

The replacement decision should account for the capacity required during normal and peak workloads. An individual machine's cost result should be considered alongside the availability of other units, expected demand and the consequences of temporarily reducing fleet capacity.

The relevant alternatives may include replacement, retention as a reserve unit, internal reallocation, rental or disposal without replacement.

Case 2.9) Equipment interdependence

Some machines operate as part of a linked production system. Their replacement should therefore be evaluated in terms of the output of the combined operation, rather than only their individual annual cost. For example, the capacity of a loading machine and the trucks serving it should be assessed together.

The comparison should identify bottlenecks, compatibility requirements and the effects of a machine's downtime on other resources. Construction equipment management addresses both individual equipment economics and production-system performance (Gransberg et al., 2006).

Case 2.10) Fleet standardisation

Replacement may affect maintenance practices, spare-parts inventories, training requirements and operational compatibility across the fleet. These wider effects should be considered alongside the individual machine's EUAC.

Standardisation should be evaluated rather than assumed to be beneficial. Any expected savings should be weighed against limitations such as reduced procurement flexibility or dependence on a particular supplier.

Case 2.11) Budget and financing

An economically attractive replacement may not be immediately affordable. The assessment should distinguish long-term economic desirability from short-term funding feasibility and compare the available acquisition arrangements.

Where purchasing, leasing or financing alternatives are assessed, their cash flows and discounting assumptions should be treated consistently. The result should identify both the preferred economic alternative and any funding constraint affecting implementation.

Case 2.12) Market conditions

Current purchase prices, actual resale offers and the availability of suitable replacement machines may differ from the assumptions used in the original model. These inputs should be updated before implementing a replacement decision.

Alternative market scenarios can be tested to determine whether the recommendation remains stable. Such testing is consistent with the sensitivity and uncertainty assessment used in equipment life-cycle cost analysis (Gransberg & O'Connor, 2015).mdl.mndot+1

Case 2.13) Strategy and contracts

A machine may remain economical for its present duties but be unsuitable for future projects or contractual requirements. The assessment should identify the required capacity, specification, operating environment and expected duration of demand.

Replacement, adaptation, rental or subcontracting should then be compared against those requirements. Where no continuing need exists, disposal without replacement should also be considered.

Case 2.14) Tax and accounting effects

Where an after-tax analysis is required, relevant tax payments, deductions and disposal effects should be reflected in the cash flows. Accounting depreciation should be distinguished from an actual cash payment; its economic relevance may arise through its effect on tax.

Book value should not replace the existing machine's current market value in a forward-looking replacement comparison. The defender's current value represents the opportunity associated with retaining rather than selling it (Jones, 2008).

If the present study uses a pre-tax model, this scope should be stated explicitly. Any later tax-adjusted comparison should use the rules applicable to the company and should not mix pre-tax and after-tax assumptions.

5.9 DISCUSSION OF RESEARCH QUESTIONS AND HYPOTHESES

5.9.1 Research Question 1 and Hypothesis H1

Q1: ***What are the main cost components that determine the economically optimal replacement timing for the equipment under study, and how do these components evolve with age and operating hours?***

Regarding the formulated question, the following hypothesis can be advanced:

H1: Escalating maintenance costs, driven by the progressive need to replace worn components and the associated downtime impacts on fleet availability, become predominant once a machine reaches a certain age or operating-hour threshold, justifying replacement before technical end-of-life for at least a subset of the fleet. The gradual nature of this cost escalation leads managers deciding on an empirical basis to postpone replacement when, objectively, it was already more than justified.

The first step in answering this question consists in splitting the total cost into two main categories: heavy equipment and trucks. Subsequently, the analysis continues by splitting these categories into families of machines, such as asphalt pavers, backhoe loaders, crawler excavators, and so on.

At category level, each category is then analysed according to its LCC components: acquisition, ownership costs, maintenance costs, and residual value. Therefore, for each category j, the following component cost is obtained:

C_{ij}= that represents the LCC component cost j in its respective machine category i.

Having all components split inside each category we now determine their relative weight in each category by simply dividing $C_{ij}$by the total cost ofe ach category i:

$$Cost\ component\ share\ =\ C_{ij}/C_i$$

The second step consists in establishing a proportional relational between cost and machine usage. A group with many machines or very high usage will naturally have bigger total costs so a correct proportion must be established. This is why we calculate costs per hour in the case of Heavy Equipment or costs per Km in the case of Trucks:

For trucks (measured in Km):

$$\text{Cost per km}_{ij} = \frac{C_{ij}}{\text{Mileage}_i}$$

For heavy equipment (measured in hours):

$$\text{Cost per hour}_{ij} = \frac{C_{ij}}{\text{Hours}_i}$$

Proceeding with these calculations for every machine category, **it is now possible to define** any machine output in terms of money spent. Instead of simply knowing how much was spent on maintenance, it is now possible to determine how much was spent on maintenance per machine output.

The third step of the answer is the most interesting. Having a 10-year dataset allows the analysis of costs per kilometre or cost per hour across each of the available 10 years and the evaluation of how these costs progress as machines get older and accumulate more working hours or kilometres on their odometers.

Calculating these unit-cost metrics year by year will show systematic shifts in component dominance with age and hours, consistent with the theoretical expectation that ownership and maintenance-related components become increasingly decisive for replacement timing as assets mature. A closer look at the evolution of these cost metrics across the study period displays a steep increase in maintenance-cost growth that overshadows any other cost component of the present LCC.

H1 is therefore supported. The composition of the life-cycle cost changes systematically with asset age and operating hours, such that different cost components dominate replacement decisions at different stages of the asset life. Overall, the results support H1 for the equipment categories in which maintenance-related costs increased clearly with age and accumulated operating hours. In these cases, the growing weight of preventive maintenance, corrective maintenance, and downtime-

related effects became more decisive for replacement timing than fuel or ownership costs alone. However, this pattern was not equally evident across the entire fleet, particularly for machines with low utilisation or incomplete historical records. Therefore, H1 is supported for at least a subset of the fleet rather than as a universal replacement rule

5.9.2 Research Question 2 and Hypothesis H2

Q2: ***What are the major challenges faced by a manager in implementing an LCC approach at enterprise level?***

Regarding the formulated question we can advance the following Hypothesis:

H2: Lack of systematized data represents the primary obstacle to effective deployment and implementation of a LCC model within a company.

The case study revealed significant constraints in linking workshop service orders, accounting entries, spare-parts invoices, equipment identifiers, operating hours, and dates across the company's information systems. These data-integration problems necessitated the manual reconciliation of thousands of records, representing a substantial and avoidable expenditure of valuable working hours. As a result, a substantial portion of preventive-maintenance costs could not be observed directly and had to be estimated using service-kit prices and prescribed operating-hour intervals to infer the timing and scope of machine interventions. The same can be said about other workshop activities, where extensive cross-checking between workshop service orders and internal accounting parts-invoicing records was required to identify incomplete or inaccurate interventions and pricing entries.

Ironically, the preparation of the LCC database showed that the main difficulty was actually not the mathematical formulation of the model but simply the identification and reconciliation of cost records. Workshop service orders frequently described the work performed without assigning a machine identification number or attaching the corresponding spare-parts invoice. Accounting records generally contained monetary amounts, but item descriptions and quantities were not always sufficiently reliable for precise classification.

This fragmentation made it difficult to match service orders and accounting entries when descriptions, amounts, dates, or machine identifiers did not correspond. As a result, some

maintenance costs had to be estimated using service-kit data, operating-hour relationships, allocation rules, or information validated through workshop knowledge.

H2 is supported because the data-preparation process demonstrated that the lack of systematized, standardized, and integrated data was a major constraint on the implementation of the LCC model. This conclusion is further supported by incomplete equipment-level cost identification, inconsistent classification of maintenance activities and expenses, and limited integration between maintenance and accounting records. These limitations increased the effort required to consolidate, validate, and allocate historical costs to individual equipment units. Consequently, the case study indicates that the main challenge is not only the availability of data, but also the absence of an integrated data-management structure that enables reliable and timely LCC-based decision-making. Overall, the results support H2. The main obstacle to implementing the LCC model was not its mathematical structure, but the lack of systematised, standardised, and integrated data linking workshop service orders, accounting entries, spare-parts invoices, equipment identifiers, operating hours, and dates. The need to reconcile these records manually increased the time and effort required to prepare reliable machine-level LCC inputs. Consequently, effective LCC deployment requires an integrated data-management structure that enables consistent cost classification, equipment-level traceability, and timely decision-making.

6
ANNEXES

6.1 APPENDIX 1 —DASHBOARD DOCUMENTATION

Table 20: Lookup and reference functions for dashboard use in Microsoft Excel

Dashboard use	Excel 2024	Excel 2016 equivalent	Excel 2007 equivalent
Find a machine's cost, age, or family	`XLOOKUP`	`INDEX` + `MATCH`	`INDEX` + `MATCH`
Vertical lookup	`XLOOKUP`	`VLOOKUP`	`VLOOKUP`
Horizontal lookup	`XLOOKUP`	`HLOOKUP`	`HLOOKUP`
Find position of a value	`XMATCH`	`MATCH`	`MATCH`
Return value from a row/column intersection	`INDEX`	`INDEX`	`INDEX`
Two-way lookup: family and year	`XLOOKUP` or `INDEX` + `XMATCH`	`INDEX` + `MATCH` + `MATCH`	`INDEX` + `MATCH` + `MATCH`
Create a dynamic dropdown list	`UNIQUE`	Helper column with `IFERROR` + `INDEX` + `MATCH`	Helper column with `IFERROR` + `INDEX` + `MATCH`

Dashboard use	Excel 2024	Excel 2016 equivalent	Excel 2007 equivalent
Get sheet or workbook name	`TEXTAFTER` / `TEXTBEFORE`	`MID`, `FIND`, `CELL`	`MID`, `FIND`, `CELL`

Table 21: Aggregation functions

Dashboard use	Excel 2024	Excel 2016 equivalent	Excel 2007 equivalent
Total LCC by equipment family	SUMIFS	SUMIFS	SUMIFS
Count machines by family or status	COUNTIFS	COUNTIFS	COUNTIFS
Average cost per hour/km by family	AVERAGEIFS	AVERAGEIFS	AVERAGEIFS
Maximum EUAC by family	MAXIFS	Array MAX(IF(...))	Array MAX(IF(...))
Minimum EUAC by family	MINIFS	Array MIN(IF(...))	Array MIN(IF(...))
Conditional total with multiple criteria	SUMIFS	SUMIFS	SUMIFS
Weighted average, e.g. cost per hour	SUMPRODUCT	SUMPRODUCT	SUMPRODUCT
Running total / cumulative LCC	SUM with expanding range	SUM with expanding range	SUM with expanding range

Dashboard use	Excel 2024	Excel 2016 equivalent	Excel 2007 equivalent
Conditional cumulative total	SUMIFS	SUMIFS	SUMIFS

Table 22: Filtering and dynamic lists

Dashboard use	Excel 2024	Excel 2016 equivalent	Excel 2007 equivalent
Extract machines needing replacement	FILTER	Helper-column flag + INDEX + SMALL + IF array	Helper-column flag + INDEX + SMALL + IF array
List unique equipment families	UNIQUE	Remove Duplicates or helper formula	Remove Duplicates or helper formula
Sort dashboard table dynamically	SORT / SORTBY	Sort manually or use helper ranking columns	Sort manually or use helper ranking columns
Create year sequence 1–10	SEQUENCE(10)	ROW(INDIRECT("1:10")) array	ROW(INDIRECT("1:10")) array
Create ranked replacement-priority list	SORT + FILTER	LARGE / SMALL + INDEX + MATCH	LARGE / SMALL + INDEX + MATCH
Count unique machines	COUNTA(UNIQUE(...))	SUMPRODUCT(1/COUNTIF(range,range))	SUMPRODUCT(1/COUNTIF(range,range))
Dashboard use	Excel 2024	Excel 2016 equivalent	Excel 2007 equivalent

Dashboard use	Excel 2024	Excel 2016 equivalent	Excel 2007 equivalent
Extract machines needing replacement	FILTER	Helper-column flag + INDEX + SMALL + IF array	Helper-column flag + INDEX + SMALL + IF array
List unique equipment families	UNIQUE	Remove Duplicates or helper formula	Remove Duplicates or helper formula
Sort dashboard table dynamically	SORT / SORTBY	Sort manually or use helper ranking columns	Sort manually or use helper ranking columns
Create year sequence 1–10	SEQUENCE(10)	ROW(INDIRECT("1:10")) array	ROW(INDIRECT("1:10")) array
Create ranked replacement-priority list	SORT + FILTER	LARGE / SMALL + INDEX + MATCH	LARGE / SMALL + INDEX + MATCH
Count unique machines	COUNTA(UNIQUE(...))	SUMPRODUCT(1/COUNTIF(range,range))	SUMPRODUCT(1/COUNTIF(range,range))

Table 23: Logical and error-handling functions

Dashboard use	Excel 2024	Excel 2016 equivalent	Excel 2007 equivalent
Replacement decision rule	IFS	Nested IF	Nested IF
Flag machine needing review	IF	IF	IF
Multiple conditions	AND, OR	AND, OR	AND, OR

Dashboard use	**Excel 2024**	**Excel 2016 equivalent**	**Excel 2007 equivalent**
Return first non-error result	IFERROR	IFERROR	IFERROR
Handle missing lookup	IFNA	IFNA	IFERROR
Switch family code to label	SWITCH	Nested IF	Nested IF
Test whether value meets all thresholds	LET + IF	IF with repeated references	IF with repeated references

6.2 APPENDIX 2 —LCC PER INDIVIDUAL MACHINE

Table 24: Individual Machine LCC (Ten-year period) - Heavy Equipment

		Units	Total Working time	ACQUISITION COSTS	Insurance	Taxes	Technical Inspections	OWNERSHIP COSTS	Preventive Labour	Preventive Parts	Reactive Labour	Reactive Parts	MAINTENANCE COSTS	TYRES TRACKS	FUEL	RESIDUAL VALUE	Total LCC NON DISCOUNTED
	LCC from Year 1	to 10	hours	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN
HEAVY EQUIPMENT																	
	Asphalt paver	**2**	**17,066**	**2,248,347**	**119,680**	**99,733**	**2,992**	**222,405**	**19,244**	**79,952**	**8,200**	**63,360**	**170,756**	**223,176**	**714,105**	**-506,287**	**110,049**
AP01	Vogele Super 1900		8,393	1,124,174	59,840	49,866	1,496	**111,202**	9,197	38,819	4,100	31,680	83,796	111,588	352,660	352,660	**53,443**
AP02	Vogele Super 1900		8,673	1,124,174	59,840	49,866	1,496	**111,202**	10,047	41,133	4,100	31,680	86,960	111,588	361,445	361,445	**56,607**
	Backhoe loader	**7**	**113,561**	**1,348,243**	**392,690**	**327,242**	**9,817**	**729,750**	**53,142**	**261,076**	**13,263**	**74,675**	**402,156**	**570,024**	**2,454,208**	**-80,153**	**1,621,777**
BL01	JCB 3CX		16,681	192,606	56,099	46,749	1,402	104,250	7,718	37,533	2,409	13,640	61,300	81,432	359,761	-40,077	**206,905**
BL02	JCB 3CX		16,545	192,606	56,099	46,749	1,402	104,250	7,514	36,963	2,409	13,640	60,526	81,432	357,795	-40,077	**206,131**
BL03	JCB 3CX		16,478	192,606	56,099	46,749	1,402	104,250	8,126	40,455	1,689	9,479	59,749	81,432	356,048	-40,077	**205,354**
BL04	JCB 3CX		16,579	192,606	56,099	46,749	1,402	104,250	7,786	38,094	1,689	9,479	57,048	81,432	356,964	-40,077	**202,653**
BL05	JCB 3CX		15,950	192,606	56,099	46,749	1,402	104,250	7,956	39,460	1,689	9,479	58,584	81,432	344,784	-40,077	**204,189**
BL06	JCB 3CX		14,801	192,606	56,099	46,749	1,402	104,250	6,698	32,603	1,689	9,479	50,469	81,432	321,786	-40,077	**196,074**
BL07	JCB 3CX		16,527	192,606	56,099	46,749	1,402	104,250	7,344	35,968	1,689	9,479	54,480	81,432	357,071	-40,077	**200,085**
	Buldozer	**3**	**49,487**	######	**179,519**	**149,599**	**4,488**	**333,607**	**53,125**	**218,995**	**14,052**	**109,087**	**395,259**	**529,656**	**1,846,666**	**-349,480**	**909,042**
BULL01	Komatsu D65 EX		15,807	775,995	59,840	49,866	1,496	111,202	17,442	71,138	4,613	35,926	129,119	176,552	593,310	593,310	**242,133**
BULL02	Komatsu D65 EX		16,804	775,995	59,840	49,866	1,496	111,202	19,431	78,273	4,613	35,926	138,243	176,552	623,409	623,409	**251,257**

BULL03	Komatsu D65 EX		16,877	775,995	59,840	49,866	1,496	111,202	16,252	69,584	4,826	37,235	127,897	176,552	629,947	629,947	**240,911**
	Crawler excavator	**6**	**101,015**	**3,307,327**	**344,074**	**286,728**	**8,602**	**639,404**	**102,578**	**435,569**	**27,480**	**290,992**	**856,619**	**1,224,288**	**3,742,423**	**-279,527**	**2440,784**
CE01	Komatsu PC240 NLC-7		16,509	609,372	59,840	49,866	1,496	111,202	15,912	68,087	4,837	50,080	138,916	188,352	604,631	604,631	**301,251**
CE02	Komatsu PC240 NLC-7		16,209	631,966	59,840	49,866	1,496	111,202	15,827	67,864	4,837	50,080	138,608	188,352	594,578	594,578	**295,855**
CE03	Komatsu PC240 NLC-7		17,724	610,168	56,099	46,749	1,402	104,250	18,564	77,846	4,066	45,336	145,812	282,528	659,312	659,312	**405,629**
CE04	Komatsu PC240 NLC-7		17,347	610,168	56,099	46,749	1,402	104,250	19,465	82,493	4,066	45,336	151,360	188,352	645,447	645,447	**317,001**
CE05	Komatsu PC240 NLC-7		16,443	610,168	56,099	46,749	1,402	104,250	16,592	70,056	4,837	50,080	141,565	188,352	613,480	613,480	**307,206**
CE06	Komatsu PC240 NLC-7		16,782	235,485	56,099	46,749	1,402	104,250	16,218	69,223	4,837	50,080	140,358	188,352	624,975	624,975	**383,961**
	Motorgrader	**6**	**73,218**	**5,177,409**	**351,556**	**292,964**	**8,789**	**653,309**	**42,109**	**161,283**	**14,780**	**90,397**	**308,569**	**366,444**	**2,051,371**	**-351,816**	**976,506**
MG01	Caterpillar 140H		11,744	774,646	59,840	49,866	1,496	111,202	6,579	25,257	2,475	14,946	49,257	40,716	329,600	329,600	**26,739**
MG02	Caterpillar 140H		11,731	787,718	59,840	49,866	1,496	111,202	7,123	26,979	2,475	14,946	51,523	40,716	329,323	329,323	**26,061**
MG03	Caterpillar 140H		13,599	856,706	59,840	49,866	1,496	111,202	8,024	30,210	2,606	15,395	56,235	81,432	373,747	373,747	**55,954**
MG04	Caterpillar 140H		12,492	856,706	59,840	49,866	1,496	111,202	7,208	27,744	2,354	14,632	51,938	81,432	345,683	345,683	**51,657**
MG05	Caterpillar 140H		11,554	950,817	56,099	46,749	1,402	104,250	6,681	26,601	2,475	14,946	50,703	40,716	329,109	329,109	**-2,172**
MG06	Caterpillar 140H		12,097	950,817	56,099	46,749	1,402	104,250	6,494	24,492	2,395	15,532	48,913	81,432	343,909	343,909	**36,754**
	Pneumatic tyre roller	**4**	**48,679**	**1,079,401**	**231,877**	**193,231**	**5,797**	**430,905**	**27,591**	**105,560**	**5,484**	**40,160**	**178,795**	**188,600**	**1,106,428**	**-110,626**	**687,674**
PTR01	Hamm GRW 18		13,059	265,831	56,099	46,749	1,402	104,250	8,517	31,834	1,371	10,040	51,762	75,440	298,034	298,034	**176,139**
PTR02	Hamm GRW 18		11,953	265,831	56,099	46,749	1,402	104,250	7,072	27,101	1,371	10,040	45,584	37,720	274,332	274,332	**132,241**

PTR03	Hamm GRW 18		12,362	273,869	59,840	49,866	1,496	111,202	6,375	24,640	1,371	10,040	42,426	37,720	277,951	277,951	**129,678**
PTR04	Hamm GRW 18		11,305	273,869	59,840	49,866	1,496	111,202	5,627	21,985	1,371	10,040	39,023	37,720	256,111	256,111	**126,275**
	Single Drum Compactor	**7**	**102,972**	**2,317,962**	**400,173**	**333,477**	**10,004**	**743,654**	**63,155**	**241,355**	**21,353**	**141,755**	**467,618**	**194,472**	**2,369,012**	**-139,747**	**1,265,997**
SSC01	Caterpillar CS583 D		15,252	335,570	56,099	46,749	1,402	104,250	9,571	39,311	5,176	33,444	87,502	22,866	395,421	-69,824	**144,794**
SSC02	Caterpillar CS583 D		14,524	336,049	56,099	46,749	1,402	104,250	8,806	35,660	5,176	33,444	83,086	22,866	379,690	-69,923	**140,279**
SSC03	Hamm 3516		14,739	324,215	56,099	46,749	1,402	104,250	8,636	31,661	2,126	13,967	56,390	29,748	324,427	-67,461	**122,927**
SSC04	Hamm 3516		14,367	324,215	56,099	46,749	1,402	104,250	8,874	33,327	2,126	13,967	58,294	29,748	315,629	-67,461	**124,831**
SSC05	Hamm 3516		15,012	324,215	56,099	46,749	1,402	104,250	8,568	32,912	2,339	16,247	60,066	29,748	328,762	-67,461	**126,603**
SSC06	Hamm 3516		14,557	336,849	59,840	49,866	1,496	111,202	9,316	34,142	2,339	16,247	62,044	29,748	312,061	-75,852	**127,142**
SSC07	Hamm 3516		14,520	336,849	59,840	49,866	1,496	111,202	9,384	34,342	2,071	14,439	60,236	29,748	313,024	-75,852	**125,334**
	Tandem Drum Compactor	**2**	**19,085**	**620,786**	**112,197**	**93,498**	**2,805**	**208,500**	**10,574**	**41,636**	**3,590**	**21,754**	**77,554**	**39,372**	**502,704**	**-129,170**	**196,256**
DSC01	Hamm HD 130		9,360	310,393	56,099	46,749	1,402	104,250	5,168	20,233	1,795	10,877	38,073	19,686	246,104	-64,585	**97,424**
DSC02	Hamm HD 130		9,726	310,393	56,099	46,749	1,402	104,250	5,406	21,403	1,795	10,877	39,481	19,686	256,600	-64,585	**98,832**
	Wheel excavator	**2**	**33,344**	**1,943,423**	**112,197**	**93,498**	**2,805**	**208,500**	**37,359**	**151,897**	**6,798**	**74,876**	**270,930**	**110,784**	**1,179,769**	**-404,378**	**185,836**
WE01	Komatsu PW180-7EO		16,468	971,711	56,099	46,749	1,402	104,250	17,221	72,548	3,399	37,438	130,606	55,392	581,395	-202,189	**88,059**
WE02	Komatsu PW180-7EO		16,876	971,711	56,099	46,749	1,402	104,250	20,138	79,349	3,399	37,438	140,324	55,392	598,374	-202,189	**97,777**
	Wheel loader	**6**	**76,002**	**5,688,147**	**340,333**	**283,611**	**8,508**	**632,452**	**90,185**	**389,894**	**18,584**	**171,198**	**669,861**	**488,244**	**2697,230**	**-385,769**	**1,404,788**

WL01	Caterpillar 962H		13,612	926,996	56,099	46,749	1,402	104,250	17,731	78,319	1,826	15,477	113,353	115,032	482,469	-192,885	**139,750**
WL02	Caterpillar 962H		11,248	926,996	56,099	46,749	1,402	104,250	14,790	63,478	1,502	13,822	93,592	57,516	404,441	-192,885	**62,473**
WL03	Caterpillar 962H		12,905	926,996	56,099	46,749	1,402	104,250	17,000	73,286	1,826	15,477	107,589	57,516	456,828	-192,885	**76,470**
WL04	Komatsu WA400		9,758	907,666	59,840	49,866	1,496	111,202	11,169	48,297	2,114	23,156	84,736	57,516	355,399	-204,390	**49,064**
WL05	Komatsu WA470-5		14,198	999,747	56,099	46,749	1,402	104,250	14,501	61,981	5,658	51,633	133,773	100,332	498,580	-208,023	**130,332**
WL06	Komatsu WA470-5		14,281	999,747	56,099	46,749	1,402	104,250	14,994	64,533	5,658	51,633	136,818	100,332	499,512	-208,023	**133,377**
	TOTAL:		**634,430**	**26,059,029**	**2,584,297**	**2,153,581**	**64,607**	**4,802,486**	**499,062**	**2,087,217**	**133,584**	**1,078,254**	**3,798,117**	**3,935,060**	**18,663,916**	**-2,736,954**	**9,798,708**

Table 25: Individual Machine LCC (Ten-year period) - Trucks

		Units	**Total Mileage**	**ACQUISITION COSTS**	Insurance	Taxes	Technical Inspections	**OWNERSHIP COSTS**	Preventive Labour	Preventive Parts	Reactive Labour	Reactive Parts	**MAINTENANCE COSTS**	**TYRES TRACKS**	**FUEL**	**RESIDUAL VALUE**	**Total LCC** UNDISCOUNTED
	LCC from Year 1	**to 10**	**Km**	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN	PLN
TRUCKS																	
	Hauling truck	16	**6,069,926**	**4,596,110**	**919,817**	**766,514**	**22,995**	**1,709,326**	**50,677**	**373,180**	**48,004**	**457,301**	**881,158**	**489,984**	**4,976,787**	**976,299**	**4,056,767**
HT01	MAN TGA 18.390 4X2		340,907	283,324	59,840	49,866	1,496	111,202	2,975	21,851	1,694	16,332	41,158	30,624	294,074	63,799	**246,784**
HT02	MAN TGA 18.390 4X2		397,671	283,324	59,840	49,866	1,496	111,202	2,771	19,968	2,722	26,061	48,800	30,624	333,843	63,799	**254,426**
HT03	MAN TGA 18.390 4X2		343,393	283,324	59,840	49,866	1,496	111,202	2,482	18,268	2,678	21,342	42,092	30,624	293,119	63,799	**247,718**

HT04	MAN TGA 18.390 4X2		338,864	283,324	59,840	49,866	1,496	111,202	2,771	19,968	2,678	21,342	44,081	30,624	290,839	63,799	**249,707**
HT05	MAN TGA 18.390 4X2		387,843	283,324	59,840	49,866	1,496	111,202	2,771	19,968	2,935	28,081	50,820	30,624	321,955	63,799	**256,446**
HT06	MAN TGA 18.390 4X2		358,309	283,324	59,840	49,866	1,496	111,202	3,179	23,734	2,722	26,061	52,974	30,624	305,909	63,799	**258,600**
HT07	MAN TGA 18.390 4X2		340,690	283,324	59,840	49,866	1,496	111,202	2,771	19,968	2,722	26,061	48,800	30,624	290,037	63,799	**254,426**
HT08	MAN TGA 18.390 4X2		357,338	283,324	59,840	49,866	1,496	111,202	2,975	21,851	2,722	26,061	50,887	30,624	297,365	63,799	**256,513**
HT09	MAN TGS 18.400 4X2		361,113	291,190	55,137	45,948	1,378	102,463	2,839	21,949	2,329	22,135	46,923	30,624	287,674	58,238	**238,248**
HT10	MAN TGS 18.400 4X2		454,007	291,190	55,137	45,948	1,378	102,463	3,247	25,715	2,722	26,061	55,023	30,624	365,545	58,238	**246,348**
HT11	MAN TGS 18.400 4X2		406,228	291,190	55,137	45,948	1,378	102,463	4,794	34,385	2,247	21,254	60,433	30,624	322,168	58,238	**251,758**
HT12	MAN TGS 18.400 4X2		402,527	291,190	55,137	45,948	1,378	102,463	3,604	25,336	3,732	32,898	61,838	30,624	316,713	58,238	**253,163**
HT13	MAN TGS 18.400 4X2		347,851	291,190	55,137	45,948	1,378	102,463	2,975	21,851	3,675	44,087	68,913	30,624	272,900	58,238	**260,238**
HT14	MAN TGS 18.400 4X2		432,517	291,190	55,137	45,948	1,378	102,463	4,284	32,966	4,455	41,400	78,650	30,624	343,107	58,238	**269,975**
HT15	MAN TGS 18.400 4X2		381,180	291,190	55,137	45,948	1,378	102,463	2,975	21,851	3,908	42,376	67,202	30,624	307,823	58,238	**258,527**
HT16	MAN TGS 18.400 4X2		419,488	291,190	55,137	45,948	1,378	102,463	3,264	23,551	4,063	35,749	62,564	30,624	333,716	58,238	**253,889**
	Tipper truck	21	**4,014,699**	**11,083,754**	**1,157,883**	**964,902**	**28,947**	**2,151,733**	**43,989**	**263,787**	**97,187**	**776,768**	**1,084,544**	**882,280**	**3,641,632**	**2,216,751**	**6,335,307**
TT01	MAN TGS 41.440 8X6		184,358	527,798	55,137	45,948	1,378	102,463	2,136	13,297	5,295	44,471	59,904	38,360	163,809	105,560	**306,287**
TT02	MAN TGS 41.440 8X6		234,028	527,798	55,137	45,948	1,378	102,463	2,719	15,936	3,065	23,814	42,469	38,360	209,803	105,560	**288,852**
TT03	MAN TGS 41.440 8X6		190,181	527,798	55,137	45,948	1,378	102,463	2,184	13,182	4,593	36,867	52,233	38,360	173,615	105,560	**298,616**
TT04	MAN TGS 41.440 8X6		179,413	527,798	55,137	45,948	1,378	102,463	1,932	11,669	3,786	39,327	52,928	38,360	162,916	105,560	**299,311**
TT05	MAN TGS 41.440 8X6		192,916	527,798	55,137	45,948	1,378	102,463	2,184	13,182	4,081	31,840	47,206	38,360	175,097	105,560	**293,589**
TT06	MAN TGS 41.440 8X6		193,700	527,798	55,137	45,948	1,378	102,463	2,184	13,182	3,511	26,489	41,855	38,360	175,730	105,560	**288,238**

TT07	MAN TGS 41.440 8X6	182,186	527,798	55,137	45,948	1,378	102,463	1,932	11,669	4,362	33,483	47,084	38,360	165,366	105,560	**293,467**
TT08	MAN TGS 41.440 8X6	159,887	527,798	55,137	45,948	1,378	102,463	1,728	10,041	4,450	31,771	43,540	38,360	146,635	105,560	**289,923**
TT09	MAN TGS 41.440 8X6	194,674	527,798	55,137	45,948	1,378	102,463	2,748	15,428	5,493	48,484	66,660	38,360	173,639	105,560	**313,043**
TT10	MAN TGS 41.440 8X6	185,690	527,798	55,137	45,948	1,378	102,463	2,136	13,297	5,150	56,382	71,815	38,360	170,247	105,560	**318,198**
TT11	MAN TGS 41.440 8X6	143,782	527,798	55,137	45,948	1,378	102,463	1,680	10,156	4,759	30,495	42,331	38,360	131,683	105,560	**288,714**
TT12	MAN TGS 41.440 8X6	183,698	527,798	55,137	45,948	1,378	102,463	1,932	11,669	5,732	41,210	54,811	38,360	167,293	105,560	**301,194**
TT13	MAN TGS 41.440 8X6	188,414	527,798	55,137	45,948	1,378	102,463	2,184	13,182	4,182	31,812	47,178	38,360	170,185	105,560	**293,561**
TT14	MAN TGS 41.440 8X6	263,124	527,798	55,137	45,948	1,378	102,463	2,971	17,449	4,757	34,596	55,016	76,720	247,180	105,560	**339,759**
TT15	MAN TGS 41.440 8X6	191,387	527,798	55,137	45,948	1,378	102,463	1,932	11,669	4,361	39,180	52,781	38,360	165,843	105,560	**299,164**
TT16	MAN TGS 41.440 8X6	253,972	527,798	55,137	45,948	1,378	102,463	2,719	15,936	5,647	40,277	58,932	76,720	229,482	105,560	**343,675**
TT17	MAN TGS 41.440 8X6	177,832	527,798	55,137	45,948	1,378	102,463	1,980	11,554	5,647	40,277	53,811	38,360	158,512	105,560	**300,194**
TT18	MAN TGS 41.440 8X6	171,443	527,798	55,137	45,948	1,378	102,463	1,164	7,795	5,069	36,486	45,445	38,360	153,826	105,560	**291,828**
TT19	MAN TGS 41.440 8X6	199,700	527,798	55,137	45,948	1,378	102,463	1,932	11,669	4,159	35,823	49,424	38,360	184,035	105,560	**295,807**
TT20	MAN TGS 41.440 8X6	184,977	527,798	55,137	45,948	1,378	102,463	1,680	10,156	4,579	39,841	51,677	38,360	169,568	105,560	**298,060**
TT21	MAN TGS 41.440 8X6	159,337	527,798	55,137	45,948	1,378	102,463	1,932	11,669	4,509	33,843	47,444	38,360	147,167	105,560	**293,827**
	Asphalt Sprayer 2	**446,111**	**983,032**	**119,680**	**99,733**	**2,992**	**222,405**	**3,213**	**21,322**	**6,175**	**45,793**	**70,328**	**49,540**	**402,228**	**221,361**	**563,634**
AS01	Mercedes-Benz Atego 2628 6X4	237,509	491,516	59,840	49,866	1,496	111,202	1,870	12,061	3,355	24,115	38,046	24,770	212,765	110,681	**284,699**
AS02	Mercedes-Benz Atego 2628 6X4	208,602	491,516	59,840	49,866	1,496	111,202	1,343	9,261	2,820	21,678	32,282	24,770	189,464	110,681	**278,935**
	TOTAL:	**10,530,736**	**16,662,897**	**2,197,379**	**1,831,149**	**54,934**	**4,083,463**	**97,879**	**658,289**	**151,366**	**1,279,862**	**2,036,030**	**1,421,804**	**9,020,647**	**3,414,412**	**10,955,709**

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[i] *AI-based language-assistance tools were used sporadically for translation and English phrasing; all output was reviewed by the author.*