Replacement Analysis for Ageing Equipment using Life-Cycle Costing
A synthesis and proposed unified replacement scheme based on real case studies

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Abstract

Ageing equipment is a recurring production systems problem because deterioration increases repair costs, downtime, and quality losses, which directly reduces effective capacity and delivery reliability. This report studies replacement decision-making using three real-world case studies and then proposes a unified scheme that can be adopted in manufacturing and fleet operations. First, we review the Texas Department of Transportation (TxDOT) Transportation Equipment Replacement Methodology (TERM), which uses life-cycle cost histories from an equipment database to compute annualized cost trends and generate auditable, class-wise ranked replacement lists under budget constraints. Second, we analyze a large road tanker truck fleet study that applies Equivalent Uniform Annual Cost (EUAC) and benefit-based criteria to estimate optimal service life and emphasizes that replacement timing is highly sensitive to realistic discount rates reflecting alternative investment opportunities. Third, we examine a gold mining conveyor belt replacement case solved using dynamic programming, demonstrating staged keep-or-replace optimization for critical assets with age-dependent economics. Building on these findings, we propose a Unified Ageing Equipment Replacement Scheme (UAERS) that combines EUAC-based economic life estimation, trend-based portfolio prioritization, and risk-aware optimization for critical assets, supported by transparent calculations and a practical implementation checklist.

Keywords: Replacement analysis, EUAC, economic life, defender-challenger, fleet replacement, dynamic programming, downtime cost.

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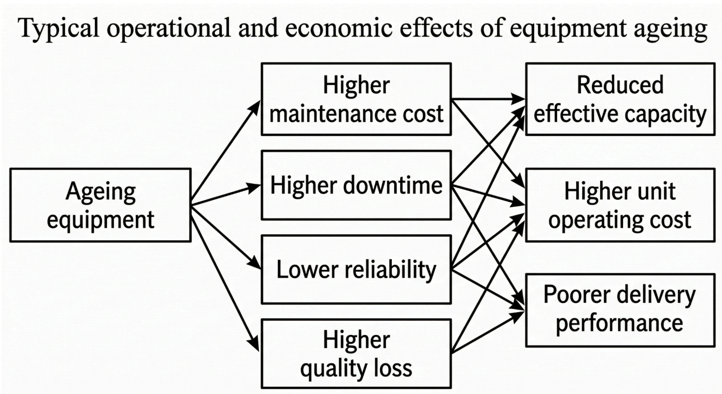
1. Introduction

Industrial assets such as machines, vehicles, conveyors, and material handling systems deteriorate with age. This deterioration is reflected in rising maintenance and repair expenditure, increasing downtime, declining operational reliability, and in many cases higher energy use and quality losses. As assets become older, their continued use can reduce effective production capacity, disturb delivery schedules, and increase the total cost of operations. The question of when an ageing asset should be replaced is therefore not only a maintenance issue, but also an important managerial and economic decision within production and operations systems.

Replacement decisions involve a fundamental trade-off. Replacing an asset too early can result in underutilization of capital and premature disposal of useful service life. Replacing it too late can expose the organization to escalating repair costs, frequent interruptions, lower productivity, and unstable operational performance. Engineering economy addresses this problem through replacement analysis, where the existing asset, commonly termed the defender, is compared against a new alternative, termed the challenger. The decision is typically made by evaluating ownership and operating costs over time and identifying the service life that minimizes the equivalent annual cost of the asset.



In practice, replacement analysis is rarely limited to a single item of equipment. Industrial organizations, fleet operators, and public agencies usually manage large groups of assets and must make replacement decisions under annual budget constraints. This requires methods that are technically sound, economically defensible, and operationally scalable. A useful replacement framework must therefore address three distinct but connected issues: estimation of economic life at the asset level, prioritization across multiple units at the portfolio level, and structured decision-making for critical equipment whose failure consequences are severe.

This report examines these issues through three real-world case studies drawn from published literature. The first is the Transportation Equipment Replacement Methodology developed for the Texas Department of Transportation, which uses life-cycle cost histories from the Equipment Operating System database to generate prioritized replacement lists for a fleet of more than 17,100 units, with about ten percent of the fleet replaced annually. The second is a case study of a large road tanker fleet belonging to the transportation arm of a major Eurasian oil company, where equivalent uniform annual cost and benefit-based methods are used to estimate optimal truck service life. The study reports that the economically optimal cut-off is highly sensitive to real discount rates and, in the fleet examined, is approximately 1 million kilometres or about 6 years of service. The third is a gold mining conveyor belt replacement study that formulates the replacement problem as a dynamic programming model, showing how staged keep-or-replace decisions can be optimized for high-consequence assets over a fixed planning horizon.

The purpose of this report is twofold. First, it presents and critically synthesizes the findings, methodologies, and decision logic of these three case studies. Second, it uses those findings to develop an integrated replacement framework for aging equipment that combines annualized life-cycle costing, portfolio-level prioritization, and risk-aware decision support for critical assets. The intent is not merely to review prior work, but to extract transferable principles and formulate a practical scheme that can be adapted to factory equipment, transport fleets, and material handling systems.

The remainder of the report is organized as follows. Section 2 reviews the theoretical foundations of replacement analysis and relevant prior work. Section 3 defines the objectives and scope of the study. Section 4 presents the three case studies in detail. Section 5 synthesizes the major findings across the cases and identifies their practical implications. Section 6 proposes the integrated replacement scheme developed in this report. Section 7 presents the supporting calculations and methodological demonstrations. Section 8 discusses the outcomes and managerial significance of the proposed approach, and Section 9 outlines future applications and scope for further development.

2. Literature Survey and Background

2.1 Foundations of replacement analysis

Replacement analysis deals with the decision of whether an existing asset should be retained in service or replaced by a new alternative. In the engineering economy, this decision is commonly framed as a comparison between the defender, which is the current asset, and the challenger, which is the proposed replacement. The underlying objective is to determine the service life or decision policy that minimizes long-run ownership and operating cost, or equivalently maximizes net economic value over the planning horizon. In the mining conveyor belt study, this idea is stated explicitly through the concept of economic life, defined as the age that minimizes average owning and operating costs, including purchase cost, operating and maintenance cost, and salvage value.

The economic logic of replacement is based on the fact that ageing assets rarely remain cost-neutral over time. As equipment becomes older, maintenance effort typically rises, productivity may decline, salvage value decreases, and the risk of disruptive failure increases. The mining study identifies reduced performance of ageing equipment, altered operating requirements, technological obsolescence, and catastrophic failure risk as major reasons for replacement, while also noting that replacement policy is closely linked to return on investment and capital budgeting decisions.

A central analytical tool in replacement analysis is annualization of life-cycle cost. Rather than evaluating only purchase price or one-year maintenance cost, the asset is assessed over time through a unified annual cost measure such as equivalent uniform annual cost. This provides a basis for comparing service-life alternatives with different cost profiles and salvage values. The truck fleet study applies this principle directly through the EUAC method and shows that annualized economic comparison remains a practical basis for service-life decisions even in large commercial fleets.

2.2 Economic life, service life, and decision criteria

The literature distinguishes between physical life, economic life, and policy-based replacement age. Physical life is the maximum age at which the asset can still function. Economic life is the age at which annualized cost is minimized. Policy-based replacement age may differ from both when organizations incorporate safety limits, operational constraints, or strategic investment opportunities. The truck fleet case is especially important in this regard because it shows that the optimal service life is not determined by repair cost alone. The authors find that the answer depends strongly on the real discount rate, interpreted as the return available from alternative investment opportunities in the trucking business. In the studied fleet, the optimal cut-off is about 1 million kilometres, or about 6 years of service, which is close to the full-service life justified on safety grounds.

This distinction is important for real industrial decision-making. A purely cost-minimizing replacement age may not always be adopted if the organization has strong growth opportunities, if safety regulations impose a stricter limit, or if downtime consequences are severe. The tanker fleet study therefore broadens traditional EUAC logic by combining cost-based and benefit-based criteria, showing that service-life decisions should reflect both operating economics and alternative uses of capital.

2.3 Replacement decisions at portfolio scale

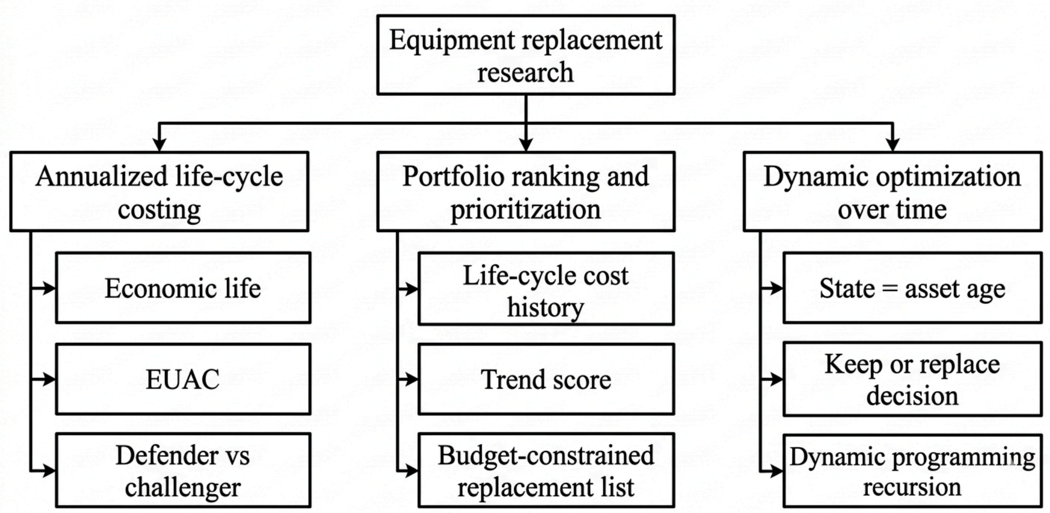
Many classical replacement models are developed at the level of a single asset. In practice, however, organizations often manage hundreds or thousands of units and replace only a fraction each year. This creates a portfolio decision problem in which managers must rank candidates, compare units within equipment classes, and operate under annual funding limits. The TxDOT Transportation Equipment Replacement Methodology is an important contribution in this direction. The report states that TxDOT maintains an active inventory of more than 17,100 units, replaces about ten percent of the fleet annually, and developed a computerized system that uses life-cycle cost histories from the Equipment Operating System database to generate prioritized replacement lists within each class.

The significance of the TxDOT methodology lies in its operational scalability. Rather than relying on subjective judgement alone, the system processes historical life-cycle cost profiles for all equipment units, applies replacement criteria, and produces tabular and graphical outputs to support decision-makers. This shifts replacement planning from isolated asset reviews to a systematic, data-driven process. In addition, the methodology introduces a trendscore derived from life-cycle cost behaviour, allowing graphical cost patterns to be converted into a usable ranking measure. This is especially relevant when replacement budgets are limited and ranking discipline becomes as important as asset-level costing.

2.4 Dynamic and staged replacement decisions

When replacement decisions are repeated over time and the consequences of failure are significant, static cost comparisons may be insufficient. In such settings, dynamic programming offers a staged decision framework in which the state of the asset, commonly its age, evolves from period to period and the decision maker chooses whether to keep or replace at each stage. The gold mining conveyor belt paper formalizes the equipment replacement problem in precisely this way. The state is the age of the conveyor belt at the start of each year, the alternatives are keep or replace, and the value function is defined as the maximum net income over the remaining planning horizon. The paper presents the recursive keep and replace equations and solves the problem over a five-year period.

Major methodological streams in equipment replacement research



This dynamic formulation is particularly suitable for critical assets because it can explicitly account for age-dependent revenue, operating cost, salvage value, and replacement cost in a multi-period setting. In the mining case, the input parameters show revenue decreasing with age, operating cost increasing with age, and salvage value declining over time. The resulting optimal policy strongly favours frequent replacement, and the authors conclude that conveyor belts in the studied system should be replaced yearly. The study therefore demonstrates how dynamic optimization can yield a clear policy rule when the economics of ageing are sufficiently strong.

Approach	Core decision variable	Typical data required	Main strength	Main limitation
Annualized life-cycle costing	Replacement age	Purchase cost, O&M cost, salvage value, discount rate	Simple and transparent	Weak on portfolio ranking and staged decisions
Portfolio ranking	Replacement priority across many units	Historical cost data, usage, downtime, repair history	Scalable under budget constraints	Less detailed at single-asset policy level
Dynamic programming	Keep or replace at each stage	Age-based revenue/cost/salvage values, planning horizon	Strong for critical staged decisions	More data- and model-intensive

2.5 Downtime, risk, and the practical limitations of simple cost models

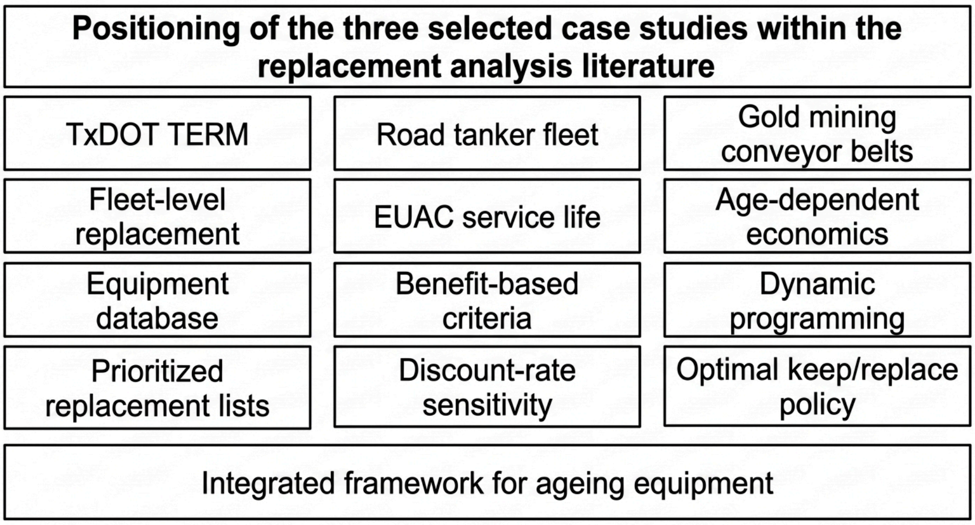
A recurring issue across the literature is that replacement conclusions depend heavily on what cost elements are included. Direct maintenance expenditure is easy to observe, but production loss from downtime is often more difficult to estimate. This matters because excluding downtime can bias the replacement age toward excessive retention of ageing assets. The TxDOT report explicitly notes sensitivity to downtime cost assumptions, while the mining conveyor belt case derives annual revenue from the daily contribution of an operating conveyor system, effectively treating downtime as lost revenue. Together, these cases show that downtime is not merely an operational nuisance; it is a core economic term in replacement analysis.

Another limitation in the literature is that no single method fully addresses all managerial needs. EUAC-style models are transparent and easy to communicate, but they are primarily asset-level tools. Portfolio systems such as TxDOT TERM improve prioritization at scale, but they are not themselves full stochastic optimization models for highly critical assets. Dynamic programming provides a stronger decision structure for staged replacement, but it is more data-intensive and may not be necessary for every asset in a plant. This suggests that an effective industrial replacement framework should combine these methods rather than choose only one.

2.6 Research gap and motivation for the present study

The reviewed literature establishes three important points. First, annualized life-cycle costing remains a sound basis for estimating economic service life. Second, large organizations need ranking mechanisms that convert asset histories into portfolio-level replacement priorities. Third, critical assets may require staged optimization rather than a single-period economic life estimate. However, the literature is fragmented: the fleet management literature emphasizes ranking and budget allocation, the engineering economy literature emphasizes annualized cost criteria, and the optimization literature emphasizes dynamic decision rules for critical assets. There is therefore a clear opportunity to integrate these strands into one coherent scheme for ageing equipment.

The present report addresses this gap by synthesizing the three selected case studies and using them to develop an integrated replacement framework. The intention is to preserve the transparency of life-cycle costing, the scalability of portfolio ranking, and the rigor of dynamic replacement policy for high-consequence assets. This synthesis forms the basis for the proposed scheme developed in the later sections of the report.



3. Objectives and Scope

The present study examines replacement analysis for ageing equipment through three real-world case studies and uses their findings to develop an integrated replacement framework. The report has two linked purposes. The first is to extract and compare the decision logic, data requirements, and major findings of the selected case studies. The second is to use those insights to propose a practical replacement scheme that can support asset-level, portfolio-level, and critical-equipment replacement decisions.

The specific objectives of the study are as follows:

1. To review the Transportation Equipment Replacement Methodology developed for the Texas Department of Transportation and identify how life-cycle cost history can be converted into ranked replacement priorities for large equipment fleets. [1]
2. To examine the road tanker truck fleet service-life study and identify how equivalent uniform annual cost and benefit-based criteria influence replacement timing under realistic discount-rate assumptions. [2]

3. To study the conveyor belt replacement model from the gold mining case and explain how dynamic programming can be used to derive a staged keep-or-replace policy for critical assets. [3]
4. To compare the three approaches in terms of method, decision level, data requirement, strengths, and limitations.
5. To develop an integrated replacement scheme for ageing equipment that combines annualized life-cycle costing, portfolio ranking, and risk-aware decision support.
6. To demonstrate the practicality of the proposed scheme through supporting calculations and implementation guidelines.

The scope of the report is limited to economic and managerial replacement analysis for ageing equipment. It focuses on cost, service life, replacement timing, prioritization, and decision structure. It does not attempt to develop a full predictive maintenance system or a real-time condition monitoring architecture. Similarly, although reliability and failure consequences are discussed where relevant, the emphasis remains on replacement decision-making rather than detailed reliability modelling. The report is intended to remain applicable to industrial equipment, transport fleets, and material handling systems where historical cost and age-related performance data are available.

The final outcome of the study is therefore not only a review of existing work, but a structured proposal for how organizations can combine these methods into a practical and transparent replacement decision process.

4. Case Studies

4.1 Case Study I: Texas Department of Transportation fleet replacement methodology

The Transportation Equipment Replacement Methodology developed for the Texas Department of Transportation addresses replacement at fleet scale. TxDOT manages an active inventory of more than 17,100 equipment units and replaces roughly ten percent of the fleet each year. To support this process, the methodology uses historical records from the Equipment Operating System database and converts them into replacement recommendations that are class-wise, repeatable, and auditable.

The core logic of the methodology is based on annualized life-cycle cost behaviour over time. Rather than evaluating a unit only on its current repair cost or age, the method studies the trend of equivalent uniform annualized life-cycle cost for each asset. The report then introduces a numerical trend score that captures the behaviour of the cost curve and allows the system to rank assets in a manner similar to human visual inspection of the graphs. This is important because replacement decisions in large fleets cannot rely on manual judgement alone; they must be converted into a scalable ranking process.

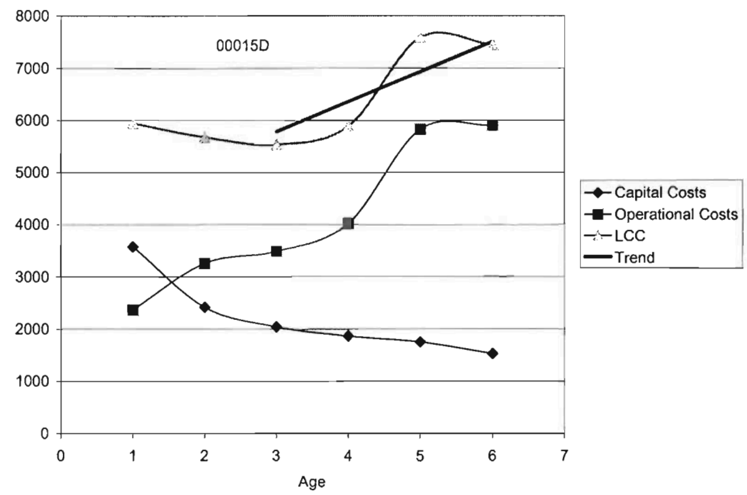


Figure 4.7 EUALCC with Increasing Trend

A key contribution of the TxDOT study is that it links asset-level cost history with fleet-level prioritization. The methodology allows managers to compare units within a class, incorporate operational attributes, and generate ranked replacement lists under budget constraints. The study also discusses sensitivity to assumptions such as downtime cost, showing that replacement priorities can shift when lost-use cost is included more explicitly. This makes the methodology especially relevant for industrial settings where repair history alone does not capture the true cost of ageing equipment.

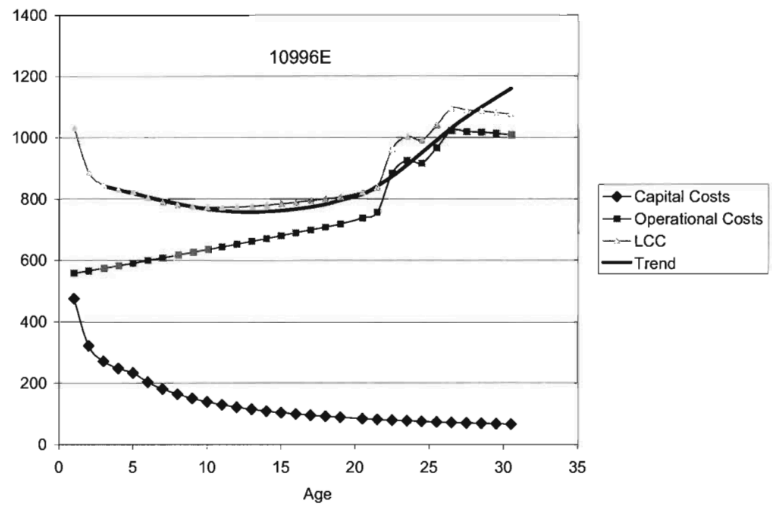


Figure 4.10 EUALCC with Combination Trend

The TxDOT case provides the portfolio-level foundation of the proposed framework. It shows how life-cycle cost data can be transformed into a structured and defensible replacement list rather than remaining a collection of isolated asset histories. In other words, it demonstrates how replacement analysis can be operationalized across a large asset base.

Table 4.1 Trendscore and EUALCC Replacement Criteria

Unit	Trendscore	Replacement Priority Based on Trendscore	Replacement Priority Based on Actual Graph Examination
10996E	43	1	1
00015D	27	2	2
00004D	0	3	3
00015D	-9.5	4	4

4.2 Case Study II: Road tanker fleet optimal service life using EUAC and benefit-based methods

The second case study examines a large road tanker fleet belonging to the transportation arm of a major Eurasian oil company. The fleet contains more than 500 trucks of similar type, which makes it suitable for service-life comparison using standardized cost and benefit criteria. The study evaluates optimal truck replacement timing using equivalent uniform annual cost together with benefit-based decision methods.

The main insight of this case is that replacement timing is highly sensitive to the discount rate used in the analysis. The study argues that the real discount rate should represent the actual return available from alternative investments in the trucking business. This means that replacement policy is not determined only by repair cost escalation or salvage decline; it also depends on what the firm could earn by deploying capital elsewhere. For the fleet examined in the paper, the optimal service-life cut-off is reported to be approximately 1 million kilometres, or about 6 years of service.

A second important contribution of the tanker fleet study is its challenge to purely cost-based replacement logic. The authors show that when benefit-based reasoning is included, especially under high-return business conditions, firms may rationally extend service life closer to the safety-based limit rather than replacing strictly at the earliest cost-minimizing age. This extends the conventional engineering economy view and makes the study highly relevant to capital-constrained industrial decision-making, where replacement must compete with other investments.

The tanker fleet case provides the economic-life and capital-allocation foundation of the proposed framework. It reinforces the use of annualized cost logic, but also warns that discount-rate choice must be realistic and context-specific. This is directly relevant when transferring replacement analysis from published case studies to factory equipment.

Table 3
Estimating the optimal service lives for trucks by means of the EUAC criterion (at E = 12%).

Useful life, T	End-of period V_t(fromTable 2)	Uniform capital recovery amount, CR_{utT}	Annual operating expenses, $OPEX_t$ (the last row of Table 1)	Present value of annual total operating expenses at discount rate E, $PV(OPEX_t)$[1]	Annual uniform operating costs $EUAC_{OPEX}$	EUAC value	Min EUAC match for T
0	92,561						
1	75,253	28,415	34,997	33,069	37,037	65,453	–
2	50,169	31,104	37,600	31,722	38,337	69,440	–
3	37,626	27,387	42,951	32,354	40,446	67,833	–
4	30,101	24,176	43,232	29,076	41,556	65,732	–
5	22,576	22,124	47,238	28,367	42,884	65,008	–
6	**12,542**	**20,968**	**48,277**	**25,885**	**43,896**	**64,863**	**MIN EUAC**

Source: analysis based on case-study data.
[1] The mid-year discounting convention is applied.

4.3 Case Study III: Gold mining conveyor belt replacement using dynamic programming

The third case study concerns conveyor belt replacement in a gold mining company in Zimbabwe. Unlike the previous two cases, which emphasize annualized cost and ranking, this study formulates the replacement problem as a dynamic programming model over a finite planning horizon. The conveyor belt age is treated as the system state, and the decision at each stage is whether to keep the existing belt or replace it with a new one.

The paper defines age-dependent annual revenue, operating cost, and salvage value for the conveyor belt system, along with the acquisition cost of a new belt. Using these values, the study develops recursive keep-or-replace equations and solves the decision problem over a five-year horizon. This formulation is important because it captures staged replacement under changing asset condition rather than reducing the entire problem to a single static annualized-cost comparison.

Table 1: Summary of input values for the revenue, operating cost and salvage value from a new conveyor belt

Age (t)	Revenue r(t)	Operating Cost c(t)	Salvage Value s(t)
0	1820000	182000	xxxx
1	1456000	236600	2750
2	1164800	397580	2475
3	931840	399854	2228
4	745472	519810	2005
5	596378	675753	1804

Key: xxxx means that there is no salvage value for a conveyor belt less than a year old.

Stage i is represented by year i, $i = 1, 2, \ldots, n$.

The alternatives at stage (year) i, call for either keeping or replacing the machine at the start of year i. The state at stage i is the age of the machine at the start of year i. Given that the machine is t years old at the start of year i, define

$f_i(t) =$ maximum net income for years $i,\ i+1, \ldots,$ and n.

The recursive equation is derived as

$f_i(t) = \max r(t) - c(t) + f_{i+1}(t+1),$ for KEEP [1]

$f_i(t) = \max r(0) + s(t) - I - c(0) + f_{i+1}(1),$ for REPLACE [2]

$f_{n+1}(.) = 0$ [3]

The results show that in the studied mining setting, frequent replacement is economically preferred. The solution tables indicate that yearly replacement minimizes overall cost for the examined operating environment, and the sensitivity analysis shows that increasing operating costs further strengthen the replacement preference. The study therefore demonstrates how dynamic programming can produce a clear replacement policy for critical assets with strong age dependence and high operational consequence.

Table 2: Alternatives in dynamic programming formulation

Stage 5	KEEP	REPLACE	Optimal	Solution
	$r(t)+s(t+1)-c(t)$	$r(0)+s(t)+s(1)-c(0)-I$	$f_5(t)$	Decision
1	1456000+2475-236600 =1221875	1820000+2750+2750 -182000-9500=1634000	1634000	R
2	1164800+2228-307580 =859448	1820000+2475+2750 -182000-9500=1633725	1633725	R
3	931840+2005-399854 = 533941	1820000+2228+2750 -182000-9500=1633475	1633475	R
4	745472+1804-519810 227466	1820000+2005+2750 -182000-9500=1633255	1633255	R
5	Must Replace	1820000+1804+2750 -182000-9500=1633054	1633054	R

Stage 4	KEEP	REPLACE	Optimal	Solution
	$r(t)-f_5(t+1)-c(t)$	$r(0)+s(t)+f_5(1)-c(0)-I$	$f_4(t)$	Decision
1	1456000+1633725-236600 = 2853125	1820000+2750+1634000 -9500-182000 = 3265250	3265250	R
2	1164800+1633478-307580 =2490698	1820000+2475+1634000 -182000-9500=3264975	3264975	R
3	931840+1633255-399854 = 2165241	1820000+2228+1634000 -182000-9500=3264725	3264725	R
4	745472+1633054-519810 = 1858716	1820000+2005+1634000 -182000-9500=4895755	4895755	R

Stage 3	KEEP	REPLACE	Optimal	Solution
	$r(t)+f_4(t+1)-c(t)$	$r(0)+s(t)+f_4(1)-c(0)-I$	$f_3(t)$	Decision
1	1456000+3264975-236600 = 4484375	1820000+2750+3265250 -9500-182000=4896500	4896500	R
2	1164800+3264505-307580 = 4121948	1820000+2475+3265250 -182000-9500=4896525	4896525	R
3	931840+3264505-399854 = 3796491	1820000+2228+3265250 -182000-9500=4895978	4895978	R

Stage 2	KEEP	REPLACE	Optimal	Solution
	$r(t)+f_3(t+1)-c(t)$	$r(0)+s(t)+f_3(1)-c(0)-I$	$f_2(t)$	Decision
1	1456000+4896525-236600 = 6115925	1820000+2750+4896500 -9500-182000= 6527750	6527750	R
2	1164800+4895978-307580 = 5660924	1820000+2475+4896500 -182000-9500=6527475	6527475	R

Stage 1	KEEP	REPLACE	Optimal	Solution
	$r(t)+f_2(t+1)-c(t)$	$r(0)+s(t)+f_2(1)-c(0)-I$	$f_1(t)$	
1	1456000+6527475-236600 =7746875	1820000+2750+6527750 -9500-182000=8159000	8159000	K

The mining case provides the policy-optimization foundation of the proposed framework. It shows that where assets are highly critical and the economics change sharply with age, a staged keep-or-replace model can be more informative than a simple economic-life estimate. This is especially useful for bottleneck or failure-sensitive industrial assets.

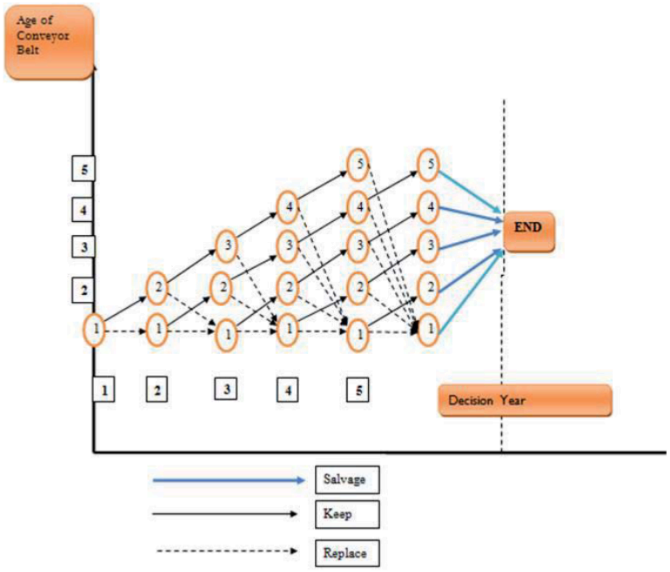


Figure 1: Summary of the network diagram representing the ERO problem for the One-Year Old machines

5. Cross-Case Synthesis and Key Insights

The three case studies collectively show that replacement analysis is not a single-method problem. Instead, it operates at three decision levels. The TxDOT methodology addresses replacement at portfolio scale by converting life-cycle cost history into ranked replacement priorities for a fleet of over 17,100 units. The road tanker study addresses service-life determination for a relatively homogeneous fleet using EUAC and benefit-based methods, and shows that the economically optimal cut-off is highly sensitive to the real discount rate, with the studied fleet indicating about 1 million kilometres or about 6 years of service. The mining study addresses staged keep-or-replace decisions for a critical asset using dynamic programming over a five-year horizon, and concludes that yearly replacement is optimal in the studied operating environment.

Case study	Decision level	Core method	Main output	Key lesson for the present report
TxDOT TERM	Portfolio or fleet level	EUALCC history, trendscore, multi-attribute ranking	Prioritized replacement list	Replacement planning must be scalable and budget-aware
Road tanker fleet	Asset class or fleet service-life level	EUAC and benefit-based methods	Optimal service-life cut-off	Discount rate selection strongly affects replacement timing

Gold mining conveyor belts	Critical asset policy level	Dynamic programming	Stage-wise keep or replace policy	Critical assets may require staged optimization, not only static cost comparison

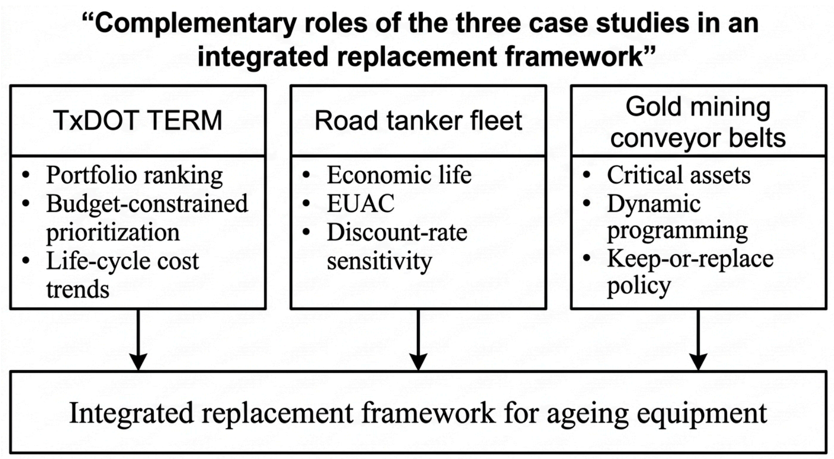
A first major insight is that annualized life-cycle costing remains the most transparent starting point for replacement decisions. Both the TxDOT and truck fleet cases rely on annualized economic logic to compare aging assets over time. This is valuable because it translates complex cost histories into a single interpretable measure and allows decision-makers to discuss replacement timing in a consistent economic language. However, the two cases also show that annualized costing alone is not sufficient. TxDOT needed an additional ranking mechanism to prioritize thousands of assets, while the truck fleet study showed that service-life conclusions change materially when the discount rate is aligned with the actual return available from alternative investments.

A second major insight is that replacement analysis must distinguish between asset-level and portfolio-level decisions. The tanker fleet case answers the question, "What is the economically appropriate service life for this class of asset?" The TxDOT case answers a different question, "Given a limited replacement budget, which units should be replaced first?" These are related but not identical problems. A practical industrial framework must therefore include both: a method for estimating economic life and a method for ranking replacement priorities across many units. The TxDOT trendscore is particularly important in this regard because it transforms life-cycle cost trend behaviour into a programmable ranking criterion that can mimic human interpretation of cost graphs.

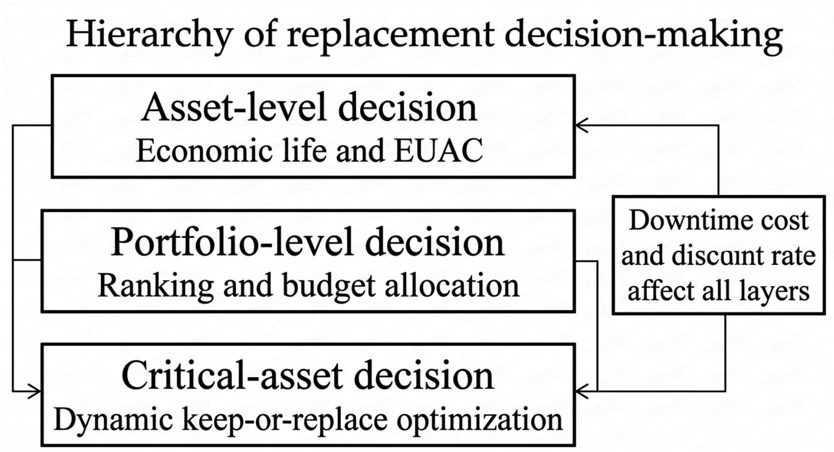
A third major insight is that critical assets may require staged decision models rather than static service-life estimates. The mining conveyor case differs from the other two studies because it explicitly models the sequence of future decisions through dynamic programming. The state of the system is the current age of the conveyor belt, and at each stage the decision-maker chooses whether to keep or replace. This is especially useful when operating cost, salvage value, and economic contribution change sharply with age. In such settings, a single annualized cost comparison may not fully capture the value of flexible staged decision-making.

A fourth major insight is that downtime is a decisive but difficult cost element. The TxDOT report shows that life-cycle cost and trendscore results are highly sensitive to downtime cost assumptions once downtime cost rises beyond modest levels. The mining study reflects the same issue indirectly by defining age-dependent annual revenue and operating cost, which means that replacement decisions are driven not only by maintenance cost but also by the economic effect of operating an ageing asset in production. This suggests that any realistic replacement framework should include downtime explicitly, while also acknowledging that downtime cost estimation is often uncertain and should be treated through sensitivity analysis rather than as a single fixed number.

A fifth insight is that no single method among the three is sufficient on its own. EUAC-style analysis is simple and communicable, but weak for prioritizing large asset portfolios. Portfolio ranking methods are scalable, but they do not by themselves provide a rigorous staged policy for highly critical assets. Dynamic programming is powerful for critical assets, but it is data-intensive and unnecessary for every unit in a fleet or plant. The main implication of the literature is therefore methodological complementarity: the strongest practical framework is one that combines annualized cost estimation, portfolio ranking, and staged optimization according to asset importance and data availability.



Based on these findings, the present study identifies the central gap in existing practice: the literature provides strong methods for separate parts of the problem, but not a single integrated scheme that can be applied across ordinary assets, fleet-scale replacement budgeting, and critical equipment. This gap motivates the integrated framework proposed in the next section of the report, where the strengths of the three case studies are combined into one structured replacement process.



6. Proposed Unified Ageing Equipment Replacement Scheme (UAERS)

6.1 Rationale for the proposed scheme

The three case studies reviewed in this report show that replacement decisions for ageing equipment operate at more than one level and cannot be addressed adequately through a single method. The TxDOT Transportation Equipment Replacement Methodology addresses replacement at portfolio scale by converting life-cycle cost histories into ranked replacement priorities for a fleet of more than 17,100 units. The road tanker fleet study addresses economic service life and shows that the replacement decision is highly sensitive to the real discount rate, with the studied fleet indicating an economically justified cut-off near 1 million kilometres or about 6 years of service. The conveyor belt case from the gold mining sector treats replacement as a staged decision problem and demonstrates how dynamic programming can identify an optimal keep-or-replace policy over a fixed planning horizon.

Taken together, these studies show that a practical replacement framework must satisfy three conditions. First, it must estimate the economic replacement age of an individual asset. Second, it must support prioritization across multiple assets when annual replacement budgets are limited. Third, it must provide stronger decision support for critical assets whose failure has severe operational consequences. These three requirements motivate the Unified Ageing Equipment Replacement Scheme, abbreviated as UAERS.

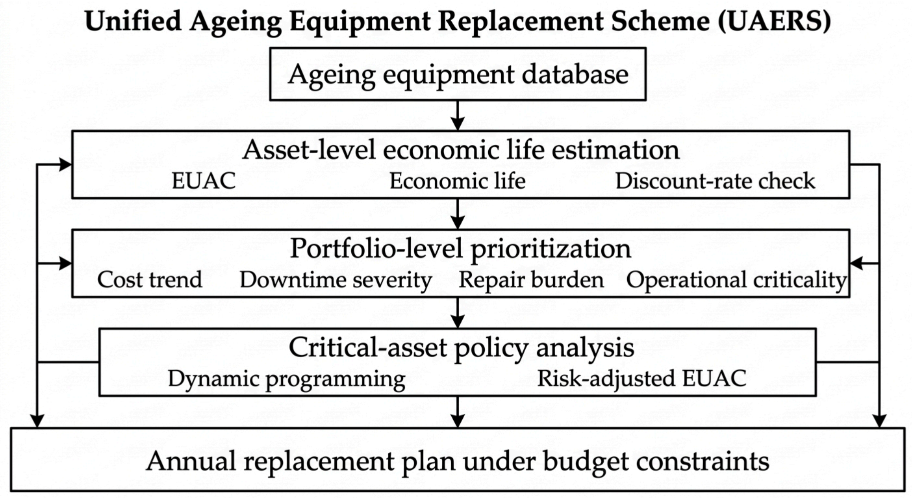
6.2 Definition of UAERS

UAERS is a three-layer framework for replacement decision-making in fleets, plants, and material handling systems. It combines annualized life-cycle costing, portfolio-level prioritization, and risk-aware policy analysis into one integrated process. The objective of UAERS is to convert historical cost and performance data into a transparent replacement plan that is economically sound, operationally defensible, and scalable across many assets.

The three layers of UAERS are:

1. **Asset-level economic life estimation**
   Each asset is evaluated to determine the replacement age that minimizes annualized total cost.
2. **Portfolio-level prioritization**
   Assets are ranked so that limited annual budgets can be allocated to the most urgent replacement candidates.
3. **Critical-asset policy analysis**
   High-consequence assets are evaluated using staged keep-or-replace logic or a risk-adjusted annualized cost approach.

This structure directly reflects the complementary contribution of the three selected case studies. The tanker fleet paper supports the economic-life layer, the TxDOT study supports the portfolio-ranking layer, and the mining conveyor study supports the staged policy layer.



6.3 Layer 1: Asset-level economic life estimation

The first layer of UAERS determines the economic replacement age of each asset using annualized life-cycle cost. For each candidate age n, the asset is evaluated using purchase cost, operating cost, maintenance cost, salvage value, and, where possible, downtime-related production loss. The preferred replacement age is the age at which annualized cost is minimized.

A generalized expression for this layer is:

$$EUAC(n) = Capital\ Recovery(n) + Operating\ Cost(n) + Maintenance\ Cost(n) + Downtime\ Cost(n)$$

This formulation is consistent with the economic logic of the road tanker fleet case, where equivalent uniform annual cost is used to compare service-life alternatives, and with the TxDOT methodology, which uses equivalent uniform annualized life-cycle cost as the basis for replacement assessment. The tanker fleet case further shows that the discount rate must reflect realistic alternative investment opportunities rather than an arbitrary nominal value, since the optimal service-life conclusion changes materially with the real discount rate.

In UAERS, this layer produces a candidate economic replacement age for every asset or equipment class.

6.4 Layer 2: Portfolio-level prioritization

A replacement age estimate is not sufficient when an organization manages many assets and can replace only a subset in a given year. The second layer of UAERS therefore converts asset histories into a ranked replacement priority list.

The TxDOT methodology demonstrates that life-cycle cost trends can be converted into a numerical ranking mechanism. Its trendscore captures the region of the annualized cost curve, the duration for which the asset has remained in that region, and the steepness of the upward trend. This allows managers to move from individual asset histories to budget-constrained fleet replacement decisions.

Building on that idea, UAERS proposes the following generalized priority score:

$$Priority\ Score\ = w1(Cost\ Trend)\ +\ w2(Downtime\ Severity)\ +\ w3(Repair\ Burden)\ +\ w4(Operational\ Criticality).$$

$where\ w1, w2, w3\ and\ w4$
are weights selected by management according to organizational priorities.

This extension is justified because the reviewed cases show that replacement decisions are influenced not only by life-cycle cost but also by operational impact. The TxDOT report discusses sensitivity to downtime cost, while the mining study reflects the economic impact of ageing through age-dependent revenue and cost. UAERS therefore treats downtime and operational criticality as explicit ranking dimensions rather than indirect side effects.

In practice, this layer generates the yearly replacement shortlist.

6.5 Layer 3: Critical-asset policy analysis

The third layer of UAERS is intended for bottleneck equipment, safety-critical assets, and equipment whose failure causes disproportionately large production losses. For such assets, a static economic-life estimate may be insufficient because the keep-or-replace choice must be revisited over time under changing age-dependent conditions.

The mining conveyor belt case provides the methodological basis for this layer. In that study, the age of the conveyor belt is treated as the system state and the decision at each stage is whether to keep the current belt or replace it. The model incorporates age-dependent revenue, operating cost, salvage value, and acquisition cost, and determines the optimal decision policy over a five-year horizon. The reported result strongly favours frequent replacement in the examined mining environment.

UAERS allows two routes for this layer:

Route A: Full staged optimization
Use dynamic programming when age-based economic data are available and the asset is sufficiently critical to justify a staged model.

Route B: Risk-adjusted annualized cost
Use a simplified risk-adjusted annualized cost when full dynamic programming is not practical.

The proposed risk-adjusted form is:

$$RA - EUAC(n) = EUAC(n) + \lambda \cdot E[Failure\ Cost(n)]$$

where λ is a managerial weight and E[Failure Cost(n)] represents the expected economic consequence of failure at age n.

This second route is the main methodological extension proposed in the present report. It serves as a practical bridge between standard annualized costing and full dynamic programming.

6.6 UAERS workflow

UAERS is implemented through the following sequence:

Step 1: Classify assets
Separate assets into ordinary assets and critical assets. Critical assets include bottlenecks, safety-relevant equipment, and assets with high downtime consequences.

Step 2: Assemble data
For each asset, compile age-wise data on purchase cost, operating cost, maintenance cost, salvage value, downtime, and usage.

Step 3: Estimate economic life
Compute annualized cost profiles and identify the candidate economic replacement age.

Step 4: Rank replacement priorities
Apply the portfolio priority score using cost trend, downtime severity, repair burden, and criticality.

Step 5: Analyze critical assets separately
Use dynamic programming or risk-adjusted annualized cost for high-consequence assets.

Step 6: Select replacements under budget constraints
Choose the final replacement set according to the available annual budget.

Step 7: Review periodically
Update the analysis using new maintenance, downtime, and operating data at each review cycle.

This workflow combines the database-driven discipline of TxDOT, the service-life realism of the road tanker study, and the staged decision logic of the mining case into a single repeatable process.

6.7 Expected outputs of UAERS

The expected outputs of UAERS are:

- annualized cost profile for each asset

- candidate economic replacement age
- ranked replacement list for the equipment portfolio
- critical-asset replacement policy
- sensitivity results for discount rate, downtime cost, and maintenance escalation
- annual replacement plan aligned with budget limits

These outputs are designed to support both technical analysis and managerial budgeting.

Layer	Main inputs	Main method	Main output
Asset-level evaluation	Purchase cost, O&M cost, salvage value, downtime cost, discount rate	EUAC or annualized life-cycle cost analysis	Candidate economic replacement age
Portfolio prioritization	Cost trend, downtime severity, repair history, criticality	Weighted ranking or trend-score based prioritization	Ranked replacement list
Critical-asset support	Age-dependent economics, failure consequences, planning horizon	Dynamic programming or risk-adjusted EUAC	Keep-or-replace policy

6.8 Advantages of UAERS

UAERS offers several advantages over using any one of the reviewed approaches in isolation.

1. It preserves the transparency of annualized life-cycle costing.
2. It scales to plant-wide or fleet-wide replacement planning.
3. It treats downtime as an explicit economic variable.
4. It provides stronger decision support for critical assets.
5. It supports yearly updating as new asset data become available.

These advantages follow directly from the complementary strengths of the three source studies.

6.9 Limitations of UAERS

Despite its practical structure, UAERS depends on the quality of the underlying data. Downtime cost estimation remains uncertain in many industrial contexts, and the TxDOT study shows that replacement outcomes can become highly sensitive as downtime assumptions increase. Dynamic programming also requires more detailed age-based input data than many organizations currently maintain. For this reason, UAERS should be implemented together with sensitivity analysis and periodic refinement of data quality rather than as a rigid one-time model.

7. Calculations and Methodological Demonstration

This section demonstrates how the proposed UAERS framework can be implemented in practice. Since the three source studies operate at different decision levels, the calculations here are presented in two compact forms. First, a generalized annualized-cost calculation is given for asset-level replacement evaluation. Second, a reproducible dynamic programming calculation from the conveyor belt case is shown to demonstrate staged keep-or-replace analysis. The purpose of this section is not to recreate every table from the source papers, but to show how their methods can be applied transparently and consistently.

7.1 Asset-level annualized cost calculation

At the asset level, replacement analysis begins with annualizing the total cost of owning and operating an asset over a candidate service life nnn. In its simplest form, the annualized cost can be represented as:

$$EUAC(n) = Capital\ Recovery(n) + Operating\ Cost(n) + Maintenance\ Cost(n) + Downtime\ Cost(n)$$

The capital recovery component may be expressed as:

$$Capital\ Recovery(n) = P(A/P, i, n) - Sn(A/F, i, n)$$

$$where\ P\ is\ initial\ cost,\ Sn\ is\ salvage\ value\ at\ age\ n,\ and\ i\ is\ the\ discount\ rate.$$

This form is consistent with the annualized life-cycle logic used in both the TxDOT methodology and the road tanker fleet study. The TxDOT report explicitly develops replacement criteria based on equivalent uniform annual life-cycle cost and examines sensitivity to discount rate and downtime assumptions. The road tanker study likewise applies EUAC and emphasizes that service-life conclusions are highly sensitive to realistic discount rates, reporting an economic service-life cut-off of about 1 million kilometres, or about 6 years of service, in the studied fleet context.

In the present report, the annualized-cost step is used as the first screening layer of UAERS. For a real plant application, the calculation would be repeated for each candidate service life using observed operating cost, repair cost, salvage value, and estimated downtime cost.

7.2 Compact demonstration of the annualized-cost logic

To keep the method operationally simple, UAERS recommends that each asset be evaluated through a structured annual cost sheet with the following fields:

- purchase cost
- salvage value at current and future ages
- annual operating cost
- annual maintenance and repair cost
- estimated downtime cost
- discount rate

The output of this sheet is the annualized cost for each candidate age and the resulting minimum-cost replacement age. This is the same logic that underlies the TxDOT life-cycle cost framework, though TxDOT applies it at fleet scale and then extends it through a ranking mechanism.

Table 7.1. Suggested annualized-cost worksheet structure

Candidate age *n*	**Purchase cost *P***	**Salvage value Sn**	**Operating cost**	**Maintenance cost**	**Downtime cost**	**EUAC**
1						
…						

7.3 Reproducible dynamic programming calculation from the mining case

The gold mining conveyor belt study provides a fully specified age-based dynamic programming model. The paper reports annual revenue r(t), operating cost c(t), and salvage value s(t) for conveyor belts aged 0 to 5 years. For example, the paper lists the following input values: for age t=1, revenue is 1,456,000, operating cost is 236,600, and salvage value is 2,750; for age t=2, revenue is 1,164,800, operating cost is 397,580, and salvage value is 2,475. The acquisition cost of a new belt is taken as 9,500.

Age t	Revenue r(t)	Operating Cost c(t)	Salvage Value s(t)
0	1,820,000	182,000	—
1	1,456,000	236,600	2,750
2	1,164,800	397,580	2,475
3	931,840	399,854	2,228

4	745,472	519,810	2,228
5	596,378	675,753	1,804

The dynamic programming structure compares two alternatives at each stage:

$Keep$: $r(t) - c(t) + fi + 1(t + 1)$

$Replace$: $r(0) + s(t) - I - c(0) + fi + 1(1)$

$where\ fi + 1(\cdot)$ is the continuation value at the next stage and I is the replacement cost.

A compact worked example can be reproduced from the one-year-old conveyor-belt solution table. For one of the evaluated states, the paper reports the following comparison:

Keep option

$1,456,000 + 6,527,475 - 236,600 = 7,746,875$

Replace option

$1,820,000 + 2,750 + 6,527,750 - 9,500 - 182,000 = 8,159,000$

Since the replace value exceeds the keep value, replacement is preferred at that stage. This is consistent with the paper's reported policy sequence, which for the two-year-old conveyor case becomes replace, replace, replace, replace, and replace, yielding a total cost of US$8,158,725.

7.4 Sensitivity considerations

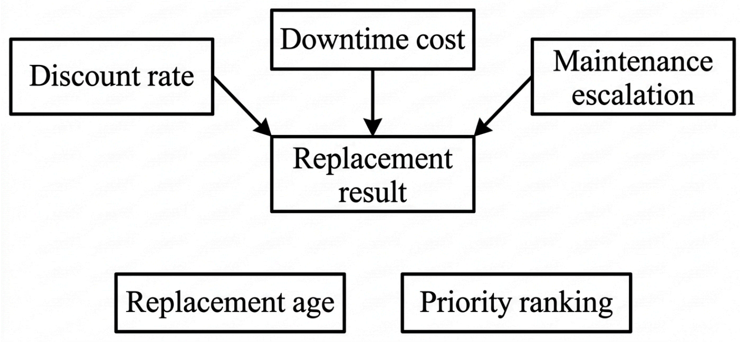
The three reviewed studies show that replacement results are highly sensitive to a small set of variables. The truck fleet study identifies the real discount rate as a critical driver of service-life conclusions. The TxDOT report shows that downtime-cost assumptions materially affect annualized life-cycle cost values and replacement trends. The mining study performs sensitivity analysis by increasing operating cost and reports that the preference for frequent replacement becomes even stronger under higher operating-cost conditions.

For this reason, UAERS recommends that every replacement analysis report at least three sensitivity cases:

- **discount rate sensitivity**
- **downtime-cost sensitivity**
- **maintenance escalation sensitivity**

These three variables are sufficient to show whether the proposed replacement age or policy is stable or highly assumption-dependent.

Recommended sensitivity variables in replacement analysis



7.5 Role of calculations within UAERS

Within the proposed scheme, the calculations in this section serve different purposes. The annualized-cost calculation supports asset-level economic-life estimation. The priority-score logic in Section 6 converts such cost results into portfolio-level ranking. The dynamic programming formulation provides stronger support for critical assets where age-dependent economics justify staged optimization. In this way, the mathematical components are not isolated exercises; they correspond directly to the three layers of UAERS and provide a practical basis for implementation.

8. Outcomes and Discussion

The three case studies show that replacement analysis becomes significantly stronger when it is treated as a structured decision system rather than as a one-time maintenance judgement. The TxDOT methodology demonstrates that life-cycle cost history can be converted into prioritized replacement lists at fleet scale, using database-backed ranking across more than 17,100 units. The road tanker fleet study shows that economic replacement timing is highly sensitive to the real discount rate and, in the studied fleet, points to an economically justified service-life cut-off of about 1 million kilometres or about 6 years. The mining conveyor-belt study shows that where asset economics vary sharply with age, staged dynamic programming can produce a clear replacement policy, with the studied system favouring yearly replacement.

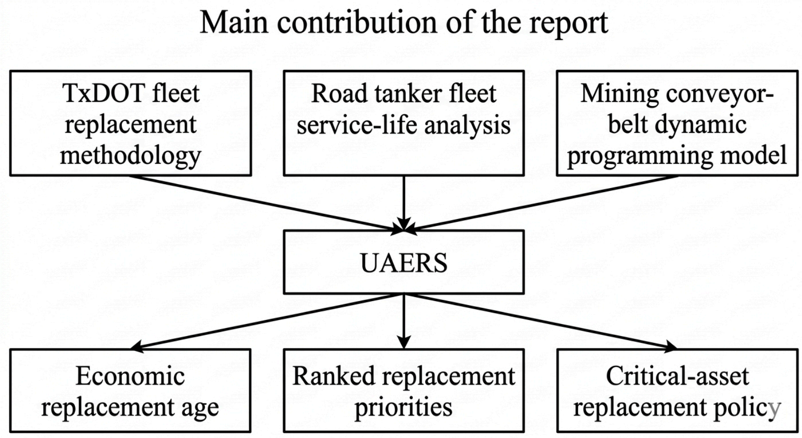
A key outcome of the present study is that these methods are complementary rather than competing. Annualized life-cycle costing provides a transparent basis for economic-life estimation, but by itself it does not solve the portfolio problem of which assets should be replaced first. Portfolio ranking methods such as the TxDOT approach solve that prioritization problem, but they are less suited for high-consequence assets that require staged optimization. Dynamic programming addresses such critical assets effectively, but it is too data-intensive to be used for every unit in a large fleet or plant. This complementarity directly supports the need for a layered framework such as UAERS.

The proposed UAERS framework therefore produces three practical outcomes. First, it provides an asset-level estimate of economic replacement age through annualized life-cycle costing. Second, it converts those asset-level results into a ranked replacement list using trend behaviour, downtime burden, repair burden, and operational criticality. Third, it reserves stronger policy analysis for bottleneck or failure-sensitive assets through dynamic programming or risk-adjusted annualized costing. This structure allows the same organization to use one coherent framework across ordinary assets, budget-constrained replacement planning, and critical equipment. The need for exactly this kind of integration is implied by the three case studies taken together.

Outcome area	**Main conclusion**
Economic-life estimation	Annualized life-cycle costing is the correct first screening step
Portfolio decision-making	Replacement must be prioritized under budget constraints
Critical assets	High-consequence assets require stronger staged analysis
Sensitivity	Discount rate, downtime cost, and cost escalation are decisive
Practical contribution	UAERS integrates these elements into one usable framework

Another important outcome is the identification of the variables that most influence replacement conclusions. Across the reviewed studies, three parameters consistently emerge as decisive: discount rate, downtime cost, and age-related operating or maintenance escalation. The road tanker study highlights discount-rate sensitivity very clearly. The TxDOT work shows that replacement trends are materially affected by downtime-cost assumptions. The mining study shows that when operating costs rise with age, replacement becomes economically preferable much earlier. This means that a replacement result should not be presented as a single fixed answer without accompanying sensitivity analysis.

From a managerial perspective, the report leads to a clear recommendation. Organizations should avoid using only age or only repair cost as replacement criteria. Instead, they should adopt a structured process in which annualized cost, downtime impact, and operational criticality are evaluated together. This improves transparency, reduces ad hoc decision-making, and makes annual budget allocation more defensible. For industrial plants, this is especially important where ageing assets influence throughput, capacity availability, and delivery performance more strongly than direct maintenance cost alone would suggest. The TxDOT study provides the strongest evidence for the value of such structured prioritization, while the other two studies show how economic-life and staged-policy analysis can strengthen the final decision.



The proposed framework also has clear practical limits. It depends on the availability and quality of historical asset data. In many organizations, downtime cost is difficult to estimate accurately, salvage values are not systematically recorded, and age-wise economic data may not be complete enough for dynamic programming. For this reason, UAERS should be viewed as a progressively implementable framework. Its first layer can be applied with modest data, while the second and third layers can be strengthened as asset-history quality improves. This staged implementability is one of its main practical advantages.

Overall, the report concludes that replacement analysis for ageing equipment should be treated as an integrated economic and operational decision problem. The reviewed case studies provide strong real-world support for annualized cost analysis, portfolio prioritization, and staged replacement policy. By combining these into UAERS, the present study moves beyond literature review and offers a practical decision structure that can be adapted to industrial equipment, transport fleets, and material handling systems.

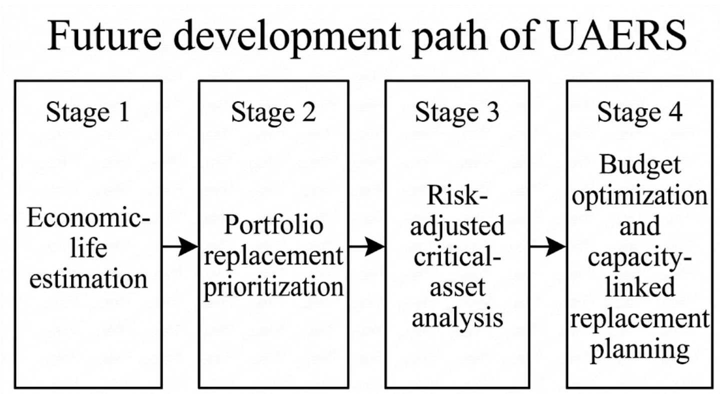
9. Future Scope and Conclusion

The present study shows that replacement analysis for ageing equipment should be treated as a structured economic and operational decision problem rather than as an isolated maintenance judgement. The three reviewed case studies collectively establish that replacement decisions involve three connected tasks: estimating economic service life, prioritizing replacement under budget constraints, and developing stronger decision policies for critical assets. The TxDOT methodology demonstrates the value of large-scale, data-backed prioritization, the road tanker fleet study shows the importance of realistic discount-rate selection in service-life analysis, and the mining conveyor-belt study illustrates the usefulness of staged optimization for critical equipment.

On the basis of these findings, this report proposed the Unified Ageing Equipment Replacement Scheme (UAERS). The main contribution of UAERS is that it integrates three decision layers into one practical framework: annualized life-cycle costing for economic-life estimation, portfolio-level ranking for budget-constrained replacement planning, and risk-aware analysis for critical assets. This structure allows organizations to avoid overly narrow criteria such as age alone or repair cost alone and instead evaluate replacement using a combination of cost, downtime impact, and operational criticality.

The framework developed in this report is directly applicable to industrial plants, transport fleets, and material handling systems where age-wise cost and performance data are available. In factory settings, it can support replacement planning for machine tools, presses, packaging lines, conveyors, compressors, and other high-use equipment. In fleet settings, it can support yearly capital budgeting and replacement prioritization across vehicle classes. In both contexts, the framework improves transparency and makes replacement recommendations easier to justify in managerial and financial discussions.

Several directions for future work follow naturally from the present study. First, the portfolio-ranking layer of UAERS can be extended into a formal optimization model that selects the best set of replacements under a fixed capital budget. Second, the risk-adjusted annualized-cost approach can be strengthened by linking it to failure-probability estimates derived from reliability or condition-monitoring data. Third, the framework can be integrated with production-planning decisions so that replacement timing is evaluated not only from a cost perspective but also from its impact on available capacity and delivery performance. These extensions would make the framework more powerful while remaining consistent with the economic foundations established in the current report.



The study also highlights an important practical caution: the quality of replacement decisions depends strongly on the quality of input data. Downtime cost, salvage value, and age-wise operating-cost trends are particularly influential, and the reviewed case studies show that replacement conclusions can shift when these assumptions change. For this reason, the report recommends that replacement decisions always be accompanied by sensitivity analysis rather than being presented as fixed outputs of a single calculation.

In conclusion, the three real-world case studies reviewed in this report provide a strong empirical and methodological basis for replacement analysis of ageing equipment. By combining their key insights into UAERS, the present work moves beyond a simple case review and offers a coherent framework that is both practically implementable and analytically defensible. The final outcome is a replacement decision scheme that can support economic-life estimation, prioritized budgeting, and critical-asset policy analysis within a single integrated structure.

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