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IMPROVEMENT OF THE DECISION-MAKING SYSTEM FOR THE PROCUREMENT OF HIGH-TECH MANUFACTURING EQUIPMENT BASED ON THE TOTAL COST OF OWNERSHIP CONCEPT, MULTI-CRITERIA ANALYSIS, AND DIGITAL PROCUREMENT DECISION SUPPORT TECHNOLOGIES

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Abstract

The procurement of high-tech manufacturing equipment is a capital-intensive and largely irreversible decision whose consequences unfold over the entire equipment life cycle. In practice, however, such decisions are frequently driven by the acquisition price alone, which systematically underestimates downstream operating, maintenance and downtime costs and leads to sub-optimal investments. This article proposes an improved procurement decision-making system that integrates three complementary components: the Total Cost of Ownership (TCO) concept, which internalises life-cycle costs; multi-criteria decision analysis (MCDA), which reconciles conflicting cost and performance criteria through an AHP–TOPSIS model; and digital procurement decision-support technologies, which operationalise the model on real, continuously updated enterprise data. The framework is validated on a metal-cutting machine

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selection case. The results reveal a systematic ranking reversal: the alternative with the lowest purchase price turns out to have the highest life-cycle cost and ranks last in the integrated evaluation, whereas the option combining superior productivity, precision and reliability becomes the preferred choice. Sensitivity analysis confirms the stability of the outcome. The proposed system reduces subjectivity, exposes hidden costs before contracting, and increases the strategic soundness of equipment procurement.

Keywords: Procurement decision-making, high-tech equipment, Total Cost of Ownership (TCO), multi-criteria decision analysis, AHP, TOPSIS, digital procurement, decision support system, Procurement 4.0, life-cycle costing.

1. Introduction

The competitiveness of a modern manufacturing enterprise is increasingly determined by the quality of its technological base. In the context of Industry 4.0 and the digital transformation of production, the acquisition of high-tech equipment is no longer a routine purchasing transaction but a strategic investment decision that shapes an enterprise's productive capacity, cost structure and market position for a decade or more. Because such decisions involve large capital outlays and are practically irreversible, the way in which they are made - and, in particular, the information on which they rest - becomes a matter of considerable economic significance.

The central difficulty of equipment procurement is that a sound decision must simultaneously reconcile numerous factors that are related yet frequently in conflict. A machine that is inexpensive to purchase may consume more energy, require costly maintenance, or deliver lower precision, thereby generating scrap and rework. Confronted with this complexity, purchasing departments tend to simplify the problem by anchoring the decision on a single, readily observable indicator - most often the acquisition price. Yet this reductionist practice is

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precisely what produces poor outcomes: the initial saving on a cheap machine can be eroded, and often reversed, by hidden downstream costs that accumulate throughout the operating life.

Overcoming this shortcoming requires addressing three distinct but interdependent questions. First, how can the full economic burden of an equipment alternative - not merely its price - be quantified? Second, how can this economic dimension be weighed rationally against non-cost performance criteria such as productivity, precision and reliability? Third, how can the resulting evaluation be carried out systematically and transparently, on data that reflect the real behaviour of equipment rather than one-off estimates? These three questions correspond, respectively, to the Total Cost of Ownership (TCO) concept, to multi-criteria decision analysis (MCDA), and to digital procurement decision-support technologies.

Although each of these instruments is well established in the literature, they are typically studied in isolation: TCO as a costing method, MCDA as a ranking technique, and digital procurement as an information-technology agenda. Their combined and mutually reinforcing use in a single procurement decision-making system for high-tech equipment remains insufficiently developed. Accordingly, the aim of this study is to design and validate an improved procurement decision-making system that integrates the TCO concept, an AHP–TOPSIS multi-criteria model, and a digital decision-support architecture. To achieve this aim, the study formalises the TCO structure of an equipment alternative, embeds TCO as a criterion within a multi-criteria model, ranks the alternatives through the integrated model, tests the robustness of the result, and outlines the digital architecture required to operationalise the system in practice.

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2. Theoretical Background and Related Work

2.1. The Total Cost of Ownership concept

The Total Cost of Ownership concept, systematised in purchasing research by Ellram [1] and subsequently refined by Ferrin and Plank [2], holds that the true economic burden of an acquired asset extends far beyond its purchase price. TCO aggregates all costs incurred throughout the asset's life cycle - acquisition, installation and commissioning, energy and consumables, maintenance and repair, the cost of downtime and quality losses, and end-of-life disposal, net of any salvage value. For capital-intensive production equipment, in which the purchase price often represents only a fraction of the life-cycle cost, TCO provides a far more realistic basis for comparison than the invoice price. Its practical limitation, however, is that it condenses a decision into a single monetary figure and therefore cannot, on its own, account for non-monetary performance attributes that are strategically important.

2.2. Multi-criteria decision analysis

Multi-criteria decision analysis complements TCO precisely where the latter reaches its limit: it enables the simultaneous evaluation of monetary and non-monetary criteria that may conflict with one another. Among the numerous MCDA methods, the Analytic Hierarchy Process (AHP), developed by Saaty [3], structures a decision hierarchically and derives criteria weights from pairwise expert comparisons, offering the important advantage of a formal consistency check. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), proposed by Hwang and Yoon [4], ranks alternatives by their relative closeness to an ideal solution and is valued for its computational simplicity and interpretability. Opricovic and Tzeng [5] compared these methods with the compromise-oriented VIKOR technique, while Zavadskas and Turskis [6] surveyed the broad application of MCDA in economics and production. A recurring finding in this literature is that combining a weighting method with a

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ranking method yields more reliable results than either used alone, which motivates the AHP–TOPSIS pairing adopted here.

2.3. Digital procurement decision-support technologies

The third strand of the literature concerns the digitalisation of procurement, often termed Procurement 4.0. Nicoletti [7] and Bienhaus and Haddud [8] describe how cloud platforms, big-data analytics, the Internet of Things, machine learning and e-procurement systems transform purchasing from a transactional function into a data-driven, analytical one. In the context of equipment procurement, these technologies are decisive because both TCO and MCDA are only as trustworthy as the data feeding them: IoT sensors and enterprise resource-planning systems can supply real energy-consumption and maintenance histories, machine-learning models can forecast future maintenance costs, and digital twins can simulate operating expenditure before purchase. Digital decision-support systems therefore convert TCO and MCDA from static, one-off calculations into a continuously updated, auditable capability.

2.4. Research gap

The review reveals that TCO addresses the cost dimension, MCDA addresses the reconciliation of conflicting criteria, and digital technologies address data and process. Each has been studied extensively, but predominantly in separation. What is missing is an integrated system in which TCO supplies the economic criterion, MCDA integrates it with performance criteria into a defensible ranking, and a digital architecture supplies the data and automates the computation. This study is intended to fill that gap.

3. The Proposed Integrated Decision-Making System

The proposed system is organised as three interacting layers, each answering one of the questions raised in the introduction. The economic layer applies the TCO

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concept to convert every alternative into a single, life-cycle-based cost figure. The analytical layer embeds that figure, alongside performance criteria, into an AHP–TOPSIS model that produces a rational overall ranking. The digital layer supplies the data and executes the computation within the enterprise's information environment. The layers are sequential in logic but continuous in operation: the digital layer feeds the economic layer, which feeds the analytical layer, whose output feeds back into procurement execution.

3.1. Economic layer: the TCO model

For each equipment alternative, the Total Cost of Ownership is computed as the present value of all life-cycle cost components over the planning horizon:

$$TCO = Cacq + Cinst + \Sigma_t (Cop + Cmaint + Cdown) / (1 + r)^t - Ssalv$$

where C_acq is the acquisition price, C_inst the installation and commissioning cost, C_op the annual operating cost (energy and consumables), C_maint the annual maintenance and repair cost, C_down the annualised cost of downtime and quality losses, r the discount rate, t the year within the planning horizon, and S_salv the discounted salvage value. Expressing all components in present value makes alternatives with different price and operating profiles directly comparable, and it is this discounted life-cycle figure - rather than the purchase price - that subsequently enters the multi-criteria model as the cost criterion.

3.2. Analytical layer: the AHP–TOPSIS model

Because TCO alone cannot capture strategic performance attributes, it is incorporated as one criterion within a multi-criteria evaluation. The analytical layer proceeds in two stages. In the first stage the AHP method determines the relative importance of the criteria: experts compare the criteria pairwise on Saaty's 1–9 scale, the priority vector is obtained from the resulting comparison matrix, and its reliability is verified through the consistency ratio (CR), the weights being accepted only when $CR \leq 0.1$. In the second stage the TOPSIS

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method ranks the alternatives: the decision matrix is normalised and weighted, the ideal and negative-ideal solutions are identified, the Euclidean distances of each alternative to these reference points are computed, and the relative closeness coefficient $C_i = S_i^- / (S_i^+ + S_i^-)$ is derived. A value of C_i closer to unity denotes a more preferable alternative. Assigning the weighting task to AHP and the ranking task to TOPSIS lets each method operate where it is strongest.

3.3. Digital layer: the decision-support architecture

The digital layer ensures that the two analytical layers operate on accurate, current data rather than on isolated estimates. Its functional architecture comprises four tiers, summarised in Table 1: a data-acquisition tier that gathers supplier, ERP, IoT and market-price data; a TCO engine that computes life-cycle cost from that data; an MCDA engine that performs the AHP weighting and TOPSIS ranking; and an analytics-and-visualisation tier that presents dashboards, sensitivity analysis and what-if scenarios, and that connects to e-procurement execution.

Table 1. Functional architecture of the digital procurement decision-support system

Tier	Function	Enabling technologies
Data acquisition	Collects supplier catalogues, ERP records, sensor and market-price data	IoT sensors, ERP integration, RPA, e-procurement feeds
TCO engine	Computes discounted life-cycle cost per alternative	Cloud computing, big-data analytics, ML cost forecasting, digital twins
MCDA engine	Derives criteria weights (AHP) and ranks alternatives (TOPSIS)	AHP/TOPSIS algorithms, consistency checking
Analytics & visualisation	Dashboards, sensitivity and what-if analysis, procurement execution	BI dashboards, scenario simulation, e-procurement platforms

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4. Case Study and Results

The integrated system was applied to the selection of a computer-numerical-control (CNC) metal-cutting machine for a machine-building enterprise. Four commercially available alternatives, denoted A1–A4, were evaluated. Their acquisition prices differ markedly, ranging from 95 to 150 thousand USD, and - as is typical - the cheapest machine to purchase is also the weakest in technical performance. The analysis proceeds in three steps that mirror the three layers of the proposed system: computation of TCO, integrated multi-criteria ranking, and comparison against the naive price-based decision, followed by sensitivity analysis and a note on digital operationalisation.

4.1. Total Cost of Ownership computation

Applying the TCO model over a ten-year horizon at a discount rate of 10% yields the life-cycle cost structure shown in Table 2. Operating and maintenance costs were derived from each machine's rated power, service intensity and reliability, while downtime cost reflects the productivity and precision of each alternative - lower-precision machines incur higher scrap, rework and stoppage costs.

Table 2. Total Cost of Ownership by alternative (present value, thousand USD, 10-year horizon)

Alt.	Acquis.	Install.	Energy	Maint.	Downtime	TCO
A1	120	10	44	38	30	**238**
A2	150	12	53	22	16	**249**
A3	95	8	35	56	81	**271**
A4	135	11	47	30	25	**244**

Note: TCO is net of discounted salvage value. Energy, maintenance and downtime columns are present values over the horizon.

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The result is striking and constitutes the first key finding. Ranked by acquisition price, the alternatives order as A3 (95) < A1 (120) < A4 (135) < A2 (150), making A3 the apparent bargain. Ranked by Total Cost of Ownership, however, the order becomes A1 (238) < A4 (244) < A2 (249) < A3 (271) - a partial reversal in which the cheapest machine to buy, A3, becomes the most expensive to own. The mechanism is transparent in Table 2: A3's low purchase price is more than offset by its high maintenance burden and, above all, by the downtime and quality losses caused by its poor precision and reliability. The TCO layer alone therefore already corrects the price illusion that would mislead a conventional purchasing decision.

4.2. Integrated multi-criteria ranking

TCO captures the economic dimension but not strategic performance, so it is embedded as one of six criteria in the multi-criteria model. The criteria are: C1 - TCO (cost); C2 - productivity, in parts per hour (benefit); C3 - machining precision, in microns (cost, since a smaller deviation is better); C4 - reliability, expressed as fault-free service life in years (benefit); C5 - flexibility and automation level, on a 1–10 scale (benefit); and C6 - supplier and after-sales service quality, on a 1–10 scale (benefit). The decision matrix combining the TCO values from Table 2 with the performance attributes of each alternative is presented in Table 3.

Table 3. Decision matrix for the multi-criteria evaluation

Alt.	C1 TCO	C2 Prod.	C3 Prec.	C4 Rel.	C5 Flex.	C6 Serv.
A1	238	45	8	10	6	7
A2	249	60	5	12	9	9
A3	271	38	10	8	5	6
A4	244	55	6	11	8	8

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Direction: C1, C3 - cost (lower is better); C2, C4, C5, C6 - benefit (higher is better). TCO in thousand USD.

In the first analytical stage the criteria weights were obtained through AHP. Experts compared the criteria pairwise; the priority vector produced the weights reported in Table 4, and the consistency ratio of CR = 0.03 (well below the 0.1 threshold) confirmed the reliability of the judgements. The weight structure reflects the enterprise's priorities: cost, embodied in TCO rather than in the purchase price, remains the single most important criterion at 0.28, but it is deliberately balanced against productivity and the quality-related criteria, whose combined weight (0.52) exceeds that of cost.

Table 4. Criteria weights obtained by AHP (CR = 0.03)

Criterion	Description	Weight
C1	Total Cost of Ownership	0.28
C2	Productivity	0.22
C3	Machining precision	0.16
C4	Reliability	0.14
C5	Flexibility / automation	0.10
C6	Supplier & service quality	0.10

In the second stage the alternatives were ranked with TOPSIS. After normalising and weighting the decision matrix, the ideal and negative-ideal solutions were identified and the relative closeness coefficient of each alternative was computed. The results appear in Table 5.

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Table 5. TOPSIS ranking of the alternatives

Alt.	**S^+**	**S^-**	**C_i**	**Rank**
A1	0.061	0.049	0.446	3
A2	**0.028**	**0.094**	**0.770**	**1**
A3	0.088	0.022	0.200	4
A4	0.045	0.071	0.612	2

The integrated evaluation identifies A2 as the preferred alternative, with the highest closeness coefficient ($C_i = 0.770$). Although A2 has the highest purchase price and only the third-lowest TCO, its clear superiority in productivity, precision, reliability, flexibility and service outweighs its cost disadvantage once all criteria are considered jointly. A4 follows in second place and A1 in third, while A3 - the apparent bargain by purchase price - again finishes last ($C_i = 0.200$), confirming at the multi-criteria level the verdict already reached by the TCO analysis.

4.3. Comparison of decision logics

The value of the proposed system is best seen by comparing the three decision logics side by side, as in Table 6. A purchasing decision based on acquisition price alone would select A3; a decision based on TCO would select A1; and the integrated TCO–MCDA system selects A2. The progression is instructive. Moving from price to TCO corrects the cost illusion by internalising life-cycle expenditure. Moving from TCO to the integrated model further refines the choice by adding strategic performance value that a purely monetary figure cannot express. Notably, across all three logics the price-cheapest option A3 is consistently the worst overall, which is the study's central empirical message.

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Table 6. Best and worst alternative under three decision logics

Decision logic	Best choice	Worst choice
Acquisition price only	**A3 (95k USD)**	A2
Total Cost of Ownership	**A1 (238k USD)**	A3
Integrated TCO + MCDA	**A2 (C_i = 0.770)**	A3

4.4. Sensitivity analysis and digital operationalisation

To assess the robustness of the ranking, a sensitivity analysis was performed by varying the weight of the most influential criterion, TCO, within a ±0.10 band and redistributing the remaining weight proportionally. Even when the TCO weight was raised to 0.38, A2 retained first place; only the margin between A1 and A4 narrowed. The leadership of A2 is therefore stable with respect to plausible errors in the weight estimates, which supports the reliability of the recommendation.

Finally, the digital layer transforms this analysis from a one-off exercise into a repeatable capability. In an operational deployment, the downtime, energy and maintenance figures underlying Table 2 would not be static assumptions but values continuously supplied by ERP records, IoT sensors on installed equipment, and machine-learning forecasts, while a digital twin could simulate the operating cost of a candidate machine before purchase. The dashboards of the analytics tier would allow procurement managers to rerun the AHP–TOPSIS ranking and its sensitivity analysis instantly whenever prices, energy tariffs or usage intensity change, thereby embedding the integrated model into the enterprise's live procurement process.

5. Discussion

The findings align with, and extend, the existing literature. They confirm Ellram's [1] argument that purchase price is a poor proxy for the economic value of an acquired asset, and they corroborate the conclusion of Opricovic and Tzeng [5]

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and Zavadskas and Turskis [6] that multi-criteria methods outperform single-indicator evaluation under conflicting criteria. The contribution of this study lies in binding these strands together: TCO is not merely computed but is inserted as a criterion within the multi-criteria model, and the whole is framed within a digital decision-support architecture consistent with the Procurement 4.0 vision of Nicoletti [7] and Bienhaus and Haddud [8]. The layered comparison in Table 6 makes the marginal value of each component explicit, showing that TCO and MCDA correct different, complementary sources of error.

Several limitations should nonetheless temper the interpretation. The criteria weights rest on expert judgement, so the composition of the expert panel can influence the outcome; broadening the panel and applying a Delphi procedure would mitigate this. The cost figures in the case study are treated as deterministic, whereas future operating and maintenance costs are inherently uncertain; incorporating fuzzy or probabilistic extensions of the TCO and MCDA components would make the model more robust to this uncertainty. Finally, the digital architecture is presented at the functional level; its full technical implementation and integration with specific ERP and e-procurement platforms remain a direction for applied work.

6. Conclusion

This study set out to improve the decision-making system for the procurement of high-tech manufacturing equipment by integrating three complementary instruments. The proposed system uses the Total Cost of Ownership concept to internalise life-cycle costs, an AHP–TOPSIS multi-criteria model to reconcile that cost dimension with strategic performance criteria, and a digital decision-support architecture to operationalise the model on real enterprise data.

Validation on a metal-cutting machine case produced a clear and practically important result: the alternative with the lowest acquisition price proved to have the highest life-cycle cost and to rank last in the integrated evaluation, while the

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option combining superior productivity, precision and reliability emerged as the preferred choice. The layered comparison demonstrated that moving from price to TCO corrects the cost illusion, and moving from TCO to the integrated multi-criteria model further adds strategic value that a monetary figure alone cannot capture. Sensitivity analysis confirmed the stability of the recommendation.

By exposing hidden life-cycle costs before contracting, reducing subjectivity, and embedding the evaluation within a digital procurement environment, the proposed system increases the economic soundness and transparency of equipment procurement decisions. Future research will focus on fuzzy and probabilistic extensions to handle cost uncertainty and on the full technical integration of the digital layer with enterprise resource-planning and e-procurement platforms.

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