



Consumable Material Costs and Their Impact on Skill Development in Welding Engineering Education: A Case Study

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ABSTRACT

BACKGROUND & CONTEXT

Welding engineering education plays a critical role in preparing skilled professionals for industries such as construction, automotive, and aerospace. Consumable materials including electrodes, filler metals, and shielding gases are essential for hands-on learning. However, constrained institutional budgets have placed significant pressure on resource allocation in training programs. The specific impact of consumable budget insufficiency on skill acquisition across training stages remains underexplored.

PURPOSE OR GOAL

This study investigates whether consumable budget allocations adequately support practical learning at each semester of a welding program at an Industrial Training Institute (ILP) in Malaysia. It further aims to develop a conceptual optimization framework aligning budget distribution with skill development outcomes.

APPROACH OR METHODOLOGY

Cost data were extracted from institutional budgeting reports for 30 students across four semesters and compared against a sufficiency threshold of RM600 per student. A one-sample t-test was applied to assess budget adequacy statistically. A multi-objective optimization model was subsequently developed integrating cost structures with learning curve parameters.

OUTCOMES

Total consumable expenditure amounted to RM311,004.50. Budget allocations in Semesters 1, 2, and 3 were statistically insufficient ($p < 0.05$), while Semester 4 met the threshold due to the higher material demands of advanced modules.

CONCLUSIONS:

Consumable sufficiency is intrinsically linked to skill development quality. A differentiated, front-loaded allocation strategy guided by multi-objective optimization is recommended to sustain both training quality and budget efficiency.

KEYWORDS

Engineering Education, Hands-on Learning, Cost Optimization, Budgeting, Skill Acquisition.

Introduction

Welding engineering stands as one of the most critical pillars of modern industrial development, serving as a key enabler of innovation and progress in multiple high-impact sectors. Industries such as construction, automotive, aerospace, and shipbuilding rely heavily on welding processes to ensure the structural integrity, durability, and safety of their products and infrastructure (Chakradhar et al.2022). As a joining technology, welding not only enhances material efficiency but also supports the creation of complex, high-performance systems that underpin national economies and global supply chains. Given its centrality, welding engineering is more than a technical process. It is a strategic capability that safeguards lives and advances industrial competitiveness worldwide (Katheria, 2021).

To sustain this role, welding engineering education plays a vital function in preparing skilled professionals who can meet the growing and evolving demands of the field. Academic institutions and vocational training centers are tasked with cultivating welders who possess both theoretical understanding and practical competence (Mahmod, et al., 2025). This dual emphasis reflects the reality that while welding involves intricate metallurgical principles, it is ultimately a hands-on craft requiring mastery through practice. Curricula are therefore designed to balance classroom-based instruction in materials science, design standards, and safety regulations with laboratory and workshop experiences that foster practical dexterity. Moreover, the increasing complexity of global industry has heightened expectations for education to align with international standards such as those set by the American Welding Society (AWS) and the International Institute of Welding (IIW), ensuring that graduates can transition seamlessly into professional roles across diverse contexts (Johnson, & Smith, 2021).

Within this educational landscape, the delivery of welding training has evolved to encompass a range of approaches, reflecting the necessity to prepare learners for modern industrial realities. Traditional training methods, such as shielded metal arc welding (SMAW) and gas metal arc welding (GMAW), remain widely used due to their foundational importance and prevalence in industry (Author, Year). These methods are typically taught in workshops where students gain experience in handling equipment, managing heat input, and achieving weld quality through repeated practice. However, with the advent of Industry 4.0, new technologies such as robotic welding systems, augmented reality (AR), and virtual reality (VR)-based simulations have been increasingly integrated into training environments (Mahmod et al, 2025). These innovations provide safer, more flexible, and resource-efficient means of instruction, while also exposing students to the digital tools and automation technologies that characterize the future of manufacturing. The integration of both conventional and emerging approaches ensures that graduates are not only proficient in core manual skills but also equipped with adaptive competencies relevant to smart factories and advanced production systems.

Despite these advancements, welding training continues to face persistent challenges that hinder its effectiveness and scalability. Safety remains a primary concern, as welding involves hazards such as burns, fumes, and electrical shocks, requiring rigorous safety protocols and specialized infrastructure [1]. Access to advanced technologies like robotic welding units or VR platforms is uneven, with many institutions unable to afford these capital-intensive investments. Furthermore, training providers often operate within constrained budgets, balancing rising costs of equipment and maintenance with the need to deliver high-quality instruction [2].Pedagogical pressures also emerge, as educators must design training models that not only meet accreditation requirements but also remain responsive to industry trends and student learning needs. These overlapping challenges underscore the importance of developing innovative and cost-effective training strategies that can sustain both access and quality in welding education.

Among the constraints faced by training institutions, the high cost of welding consumables emerges as one of the most pressing and under-addressed barriers. Consumables such as

electrodes, filler metals, and shielding gases represent recurring expenses that accumulate significantly over the course of training programs [3]. Unlike capital equipment, which can serve multiple cohorts over extended periods, consumables are depleted rapidly through hands-on practice. This financial burden directly restricts the amount of workshop time students can access, curtailing their opportunity to gain the repetition and precision required to achieve welding competence. In resource-constrained institutions, especially those in developing contexts, the cost of consumables often forces trainers to limit practice sessions, thereby undermining skill acquisition and reducing graduate readiness for industry demands (Author, Year). This issue not only affects individual learning outcomes but also weakens the overall pipeline of skilled welders, raising broader concerns about workforce development and industrial competitiveness. Addressing the high cost of welding consumables is therefore critical to ensuring that welding training programs remain accessible, effective, and aligned with the needs of modern industry.

Literature Review

Skill Development in Engineering, and Technology Related Program

Skill development faces numerous challenges, including identifying necessary skills, ensuring effective training, and measuring its impact. Other obstacles include a lack of resources, inadequate opportunities to apply new skills, and engaging learners. These challenges are further compounded by factors like organizational changes, diverse learning styles, and the need to contextualize training programs. One of the foremost challenges in skill development is identifying the right set of competencies that align with both current industry needs and future labor market demands. The issue of a skills gap arises when there is uncertainty about the specific technical and non-technical skills required for particular jobs, or when existing employees do not fully possess them. In welding education, for instance, industries often require graduates to be proficient not only in manual metal arc (MMA) or gas tungsten arc welding (GTAW) techniques, but also in the use of automated welding machines, quality inspection, and adherence to safety standards. However, many training institutions still prioritize conventional welding techniques, resulting in graduates who are competent in basic operations but lack exposure to advanced or industry-relevant practices. This challenge is compounded by evolving needs in the labor market, where rapid technological advancement and the introduction of automation and robotics continually reshape the skills expected of workers. A welder who was trained five years ago may find that their knowledge is insufficient for modern contexts, such as working with computer-numerical-controlled (CNC) welding systems or advanced materials like stainless steel and alloys. As a result, institutions must continuously review and update their training curricula to keep pace with these shifting demands. The difficulty of bridging the gap between education providers and industry expectations further reinforces the problem. Educational institutions often operate with outdated equipment or limited consumable materials, making it difficult to simulate authentic workplace conditions. For example, while employers may expect welders to master high-quality finishing under time constraints, students may only practice on a restricted number of metal plates due to budgetary limitations. This gap not only affects graduate employability but also forces industries to invest additional resources in retraining new hires to meet production standards.

Designing and delivering effective training in welding education presents another critical challenge. Learners come with diverse learning styles, where some prefer visual demonstrations, others may learn best through hands-on practice, and some may benefit from structured theoretical explanations. Training programs that fail to consider these differences risk leaving certain groups of learners behind. Another pressing concern is maintaining engagement. Welding, especially in its early stages of training, requires repetitive practice, which can lead to reduced concentration and shorter attention spans among students. For instance, learners become disengaged if training is limited to theoretical lectures or monotonous simulations without real-world application. Contextualization of training is equally

important, as welding practices vary according to industrial needs and workplace settings. A trainee who learns in a generic training environment may face difficulties when transitioning to specialized sectors, such as automotive or shipbuilding industries, where techniques and safety requirements differ. Furthermore, accessibility remains a significant issue, particularly in regions where training centers are limited or resources are insufficient. Students from rural areas, for example, may not have the same opportunities to access welding facilities as those in urban training institutes. These challenges highlight the need for carefully designed, inclusive, and context-specific training programs that can effectively prepare learners for real industrial demands.

Measuring and improving training outcomes in welding education is another major challenge that requires careful consideration. One key issue is impact measurement, as it is often difficult to determine whether training programs truly enhance learners' competencies or improve their job performance. For instance, while a student may perform well in a simulated welding exercise, this does not always translate into consistent quality when applied in real-world industrial settings. Similarly, return on investment (ROI) remains a critical concern, as institutions and stakeholders often demand clear evidence of how training contributes to productivity, safety, and employability. However, welding training programs require substantial investment in equipment, consumables, and instructor expertise, making it challenging to demonstrate immediate or quantifiable financial benefits. Continuous improvement also poses difficulties, since welding techniques, industry standards, and technological tools evolve rapidly. Training curricula and methods must therefore be regularly updated to remain relevant, yet many programs face delays in revision due to limited resources or bureaucratic constraints. Without systematic evaluation and refinement, training programs risk becoming outdated, reducing their effectiveness in preparing learners for industry needs.

Besides, the issue of budget sufficiency in engineering education has received increasing attention in both academic and practice-oriented research. Numerous studies highlight that effective engineering training that particularly in disciplines requiring intensive laboratory or workshop components such as welding, manufacturing, and materials engineering which demands significant investment in consumables, specialized equipment, and ongoing maintenance (Prince, 2004; Sheppard et al., 2009; Johri & Olds, 2011). Accurate cost estimation and resource planning are therefore critical to ensure that institutions can meet curriculum standards while sustaining financial viability. Research has shown that many engineering programs often rely on reactive budgeting practices, where resource allocation is not fully aligned with actual instructional demands. This misalignment can lead to underfunding of laboratory and workshop modules, thereby compromising students' access to essential hands-on learning opportunities (Felder & Brent, 2016). Other scholars argue for performance-based and outcomes-oriented budgeting frameworks that explicitly tie expenditure to measurable learning achievements, ensuring that financial resources contribute directly to competency development (Freeman et al., 2014). International perspectives also indicate that one-size-fits-all funding models are insufficient for engineering education, where training costs vary widely across programs. For instance, laboratory-intensive courses such as welding and fabrication are particularly resource-heavy due to their reliance on consumables, safety equipment, and industrial-grade tools (Raza et al., 2019). In Australia, studies on engineering and applied sciences education have revealed significant inefficiencies in institutional spending, suggesting that cost savings of 9% to 33% could be realized if best practices were consistently adopted (Fieger et al., 2017).

Moreover, cost-benefit analyses in higher education emphasize that financial sufficiency should not only be considered from an expenditure standpoint but also in relation to return on investment, student competency, and graduate employability (Johanson & Van Adams, 2004; Graham, 2018). These perspectives call for a more granular approach to modeling costs in engineering education, one that accounts for module-specific resource needs, equipment depreciation, and fluctuating material prices. Taken together, the literature underscores the urgency of developing more dynamic, data-driven, and program-sensitive budgeting

frameworks for engineering education. Such approaches are necessary not only to deliver high-quality training but also to sustain institutional effectiveness and ensure that graduates enter the workforce with strong, industry-relevant competencies.

Case Study: Cost Analysis of Consumable Materials in Welding Training

This case study focuses on the cost analysis of consumable materials in welding training at an Industrial Training Institute (ILP), where increasing student enrolment directly influences both the availability of resources and the effectiveness of skill development. As more students join the program, the demand for consumable materials such as electrodes, shielding gases, and base metals rises significantly, placing pressure on training budgets and resource allocation. Figure 1 presented the overview of the methodology that aimed to determine the cost analysis for a selected program in ILP. The process starts with a selected program P_1 , which consists of multiple semester, $S = S_1, S_2, S_3, \dots, S_n$. Each of semester, S_i includes a set of modules and cost of consumable materials, $S_i M_i = S_{i1} M_{i1}, S_{i1} M_{i2}, S_{i1} M_{i3}, \dots, S_{i1} M_{in}$. For every semester the data was collected S_i , a corresponding cost SC_i is estimated based on the total cost of all modules. These cost are aggregated and compared to the allocated program budget, $BP_i = BP_1$, to determine the budget gap. The final step involves analysis, modelling, and optimization to improve resource allocation and effectively address any budget gaps. This phase is currently in progress and will be expanded to include other programs for comparison and further improvement.

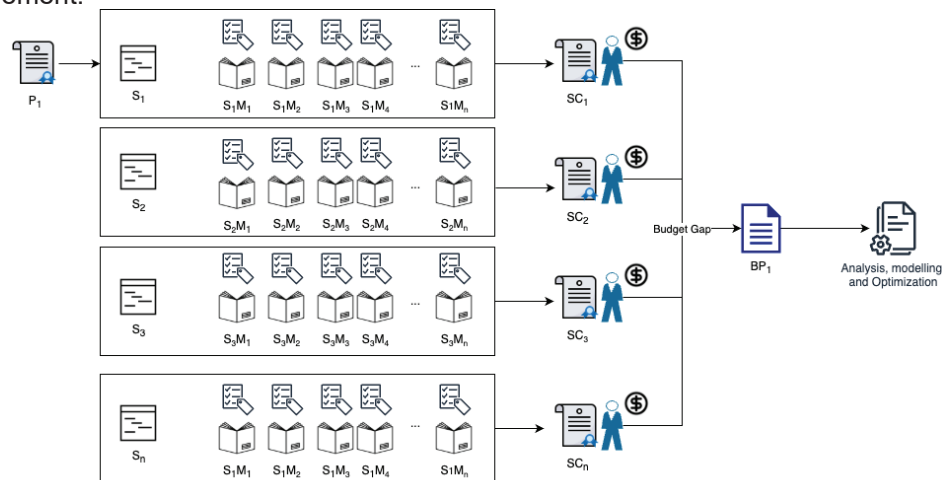


Figure 1: Methodology framework for consumable cost analysis and budget gap determination

Data Extraction

A comprehensive cost analysis was conducted to assess the sufficiency of the allocated budget for practical welding training at ILP based on the annual budgeting report. The total expenditure on consumable materials for 30 students over four semesters was RM311,004.50, resulting in an average cost of RM10,366.82 per student. Table I presents the semester-wise breakdown of per-student costs. Semester 4 incurred the highest cost (RM4,296.40), followed by Semesters 2 (RM2,346.03), 3 (RM2,263.03), and 1 (RM1,461.36). The increasing cost trend reflects the complexity and material intensity of advanced modules, particularly those involving stainless steel and carbon steel pipe welding. For instance, the SMAW Process; Carbon Steel Pipe 3 module alone accounted for RM1,333.48 per student, indicating a high material demand for specialized pipe welding tasks. Such disparities highlight the limitations of a uniform budget distribution approach and call for a differentiated, evidence-based allocation model.

Table 1: Extraction of consumable materials costs

Sem	Cost Module (RM)/Student					Total Cost (RM)	Mean Cost	Standard deviation
	A	B	C	D	E			
1	189.81	380.13	241.21	650.21	00.00	1,461.36	292.27	242.05
2	251.17	205.14	1,008.33	414.64	466.74	2,346.03	469.20	320.51
3	537.79	587.15	597.55	375.09	165.45	2,263.03	452.61	183.60
4	543.31	1,333.48	721.04	650.98	1,047.58	4,296.40	859.28	325.06

In Semester 4, the most resource-intensive modules were observed, contributing significantly to the overall training cost. Notably, the SMAW Process – Carbon Steel Pipe 3 (Module A08-44-21) incurred the highest cost per student at RM1,333.48, amounting to RM40,004.42 for a cohort of 30 students. This was followed by the GTAW and SMAW Combination Process (A08-44-24) at RM1,047.58 per student. Other costly modules included SMAW Process – Carbon Steel Pipe 4 (RM721.04), GTAW Process – Carbon Steel Pipe (RM650.98), and Fabrication Work (RM543.31). These modules involved advanced pipe welding techniques and multi-process applications, which require a higher volume of consumables and complex equipment handling, thus justifying their elevated cost structure as summarized in Table 2. (Detailed module descriptions are partially summarized due to space constraints).

Table 2: Cost breakdown of semester 4 welding modules (partial list)

No. Semester	Module Code & Title	Cost per Student (RM)	Total Cost for 30 Students (RM)
1	A08-24-25: Fabrication Work	543.31	16,299.35
2	A08-44-21: SMAW Process – Carbon Steel Pipe 3	1,333.48	40,004.42
3	A08-44-22: SMAW Process – Carbon Steel Pipe 4	721.04	21,631.12
4	A08-34-23: GTAW Process – Carbon Steel Pipe	650.98	19,529.51
5	A08-44-24: GTAW and SMAW Combination Process	1,047.58	31,427.55

Table 3 presented the hypothesis testing using one sample t-test on consumable cost per student. The method used is one-sample t-test, which is a common statistical test to compare the sample mean against a known or target value. In this case, the sample is the cost per student for each semester (five cost modules), and the target value is the required budget of RM600 per student. For each semester (Sem 1 to Sem 4), we conducted a one-sided t-test with the following hypothesis, Null Hypothesis (H_0): Mean cost per student is greater than or equal to RM600 (sufficient) and Alternative Hypothesis (H_1): Mean cost per student is less than RM600 (insufficient). We used a significance level of 0.05 ($\alpha = 0.05$).

Table 3: One-sample t-test on mean consumable cost per student

Semester	Mean Cost (RM)	p-value	Conclusion
Sem 1	292.27	0.0006	Budget insufficient
Sem 2	469.21	0.0488	Budget insufficient
Sem 3	452.61	0.0255	Budget insufficient
Sem 4	859.28	0.9544	Budget sufficient

From the analysis, Sem 1, Sem 2, and Sem 3 show significant evidence ($p < 0.05$) that the mean cost per student is below RM600, confirming that the budgets are insufficient. Sem 4

has a mean cost above RM600, and the p-value is high ($p > 0.05$), so we fail to reject the null hypothesis. This means the budget in Semester 4 is considered sufficient. As a conclusion, this analysis shows that budget allocations in Sem 1, Sem 2, and Sem 3 are statistically insufficient when compared to the required RM600 per student. Only Semester 4 meets the sufficiency requirement. This suggests that budget planning for earlier semesters need to be revised or increased to ensure students receive adequate support. Figure 2 presented a bar chart to visualize the mean costs per semester and compare them with the required budget line. From the welding education perspective, these findings underscore how consumables are not merely financial considerations but essential pedagogical resources. Consumables function as the medium through which experiential learning takes place, enabling students to convert theoretical knowledge into practice. A shortage of consumables in the early semesters directly restricts opportunities for hands-on engagement, weakening the effectiveness of the curriculum in cultivating problem-solving ability, precision, and safety awareness. Moreover, the statistical evidence highlights the need for resource planning that is aligned with the developmental trajectory of skill acquisition. Instead of applying uniform budget allocations across semesters, engineering programs should consider differentiated resource strategies that match the intensity of practice required at each stage of learning. A front-loaded investment in consumables during the earlier semesters could strengthen students' foundational skills, enabling them to transition more effectively into advanced modules. This approach would not only improve technical competence but also foster greater confidence and readiness for industry expectations. In summary, the analysis demonstrates that consumable sufficiency is intrinsically linked to skill development in welding education. Budgetary shortfalls in earlier semesters represent more than a financial issue; they are an educational challenge that undermines the progression of student learning. Addressing these gaps through more strategic allocation of consumables can ensure that students experience a continuous and balanced learning pathway, ultimately improving their mastery of welding skills and their preparedness for professional practice

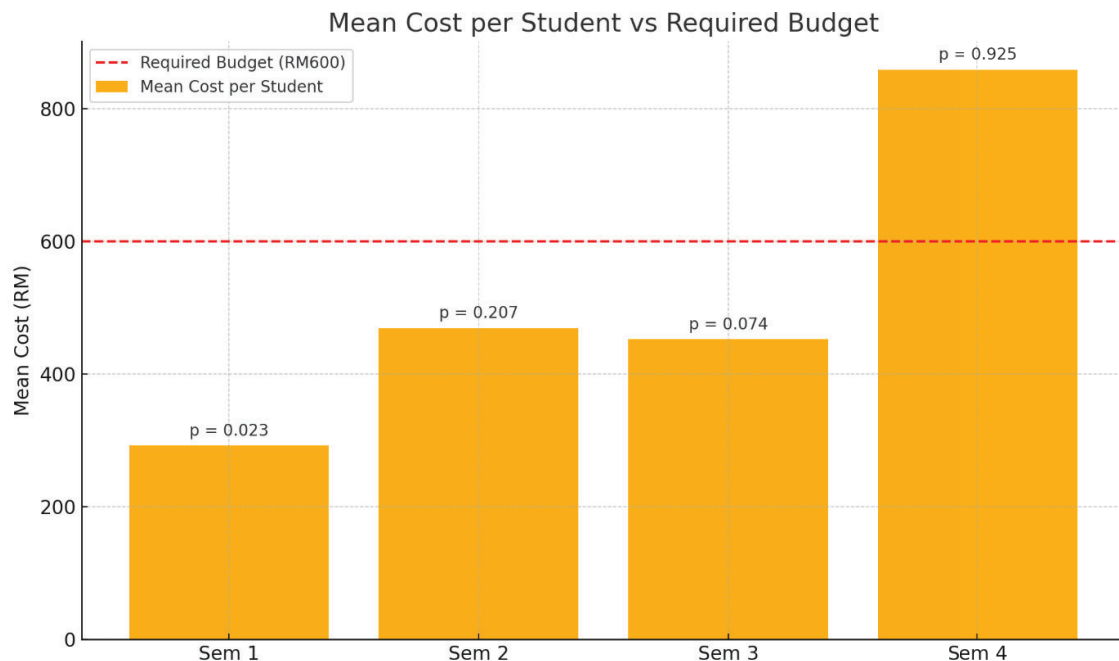


Figure 2: Bar chart of hypothesis testing

Conceptual Modelling Framework

In this section presented the working in progress of conceptual modelling framework which is aimed to optimize the relationship between budget allocation and skill acquisition in welding training using multi-objective optimization approach. This conceptual framework recognizes that the delivery of welding modules is influenced not only by pedagogical considerations but also by the availability of consumables and the financial resources allocated each semester. This study will integrate the cost structures with skill development dynamics, which the model provides a systematic way to analyze trade-offs and identify efficient training strategies. In the model, three main sets are considered. The set of trainees is denoted by $i \in I$, the set of welding modules by $j \in J$, and the set of consumables, $m \in M$. Each semester $s \in S$ includes a defined subset of modules, $J_s \subseteq J$. For example, in Semester 1 the modules may cover fundamental Shielded Metal Arc Welding (SMAW) practices, while later semesters extend to advanced SMAW, Gas Metal Arc Welding (GMAW), and Gas Tungsten Arc Welding (GTAW). The parameters of the model are grounded in the training cost structure. A total budget for each semester is represented as B_s . Fixed costs, such as instructor salaries and equipment upkeep, are expressed as F and MNT . Variable costs depend on the amount of consumables used, with c_t representing the unit cost of training time and c_m representing the unit cost of consumable type m . Each module has requirements in terms of practice time and consumables per repetition, captured by α_j and β_{jm} , respectively. In addition, skill development is characterized by a learning curve, with parameters A_j (the maximum attainable skill in module j), r_j (the rate of learning), and n_j^{mid} (the practice dose needed to reach 50 percent of the maximum skill). Weighting coefficients γ_j and δ_{jm} are used to link training time and consumable use to effective practice dose. Minimum skill thresholds, denoted as S_j^{min} , may be required for certification, while specific targets, S_j^{target} , will be imposed to guide competency goals.

The decision variables capture how resources are allocated and how skills evolve. The variable x_{ij} represents the proportion of module j completed by trainee i , where a value of one indicates that the trainee completes the full prescribed practice for that module. The training hours allocated to each trainee and module are denoted by h_{ij} , while the consumables used are represented by u_{ijm} . From these allocations, the effective practice dose is calculated as n_{ij} and the corresponding skill level attained is given by s_{ij} . To account for deviations from defined targets, a slack variable ξ_{ij} is introduced to measure the skill shortfall for trainee i in module j . The financial structure of the training program is expressed through the total cost function. The total cost of training is equal to fixed costs plus maintenance costs, together with the sum of all training hours multiplied by their unit cost and the sum of all consumables multiplied by their respective unit costs as presented in Equation 1.

$$C_{\text{total}} = F + MNT + \sum_{i \in I} \sum_{j \in J} \left(c_t h_{ij} + \sum_{m \in M} c_m u_{ijm} \right) \quad (1)$$

Each semester is subject to a budget constraint, such that the cumulative cost of all training activities in semester s does not exceed the available allocation B_s .

Besides, Skill acquisition is modeled through a logistic learning function. The effective practice dose, defined as a combination of training hours and consumable use as presented in Equation (2) and the corresponding skill level is as presented in Equation (3), respectively.

$$n_{ij} = \gamma_j h_{ij} + \sum_{m \in M} \delta_{jm} u_{ijm} \quad (2)$$

$$s_{ij} = \frac{A_j}{1 + \exp \left[-r_j (n_{ij} - n_j^{\text{mid}}) \right]} \quad (3)$$

Furthermore, this multi-objective problem is operationalized based on the two strategies. A weighted-sum approach combines the objectives into a single function, where policy-driven weights determine the emphasis on cost, skill, and target achievement. In this case, the objective is shown in Equation (4). Alternatively, an epsilon-constraint approach may be used, where one objective is optimized while the others are bounded by threshold values. For instance, the model may maximize total skill while constraining costs to remain within budget and limiting total skill shortfall to an acceptable level.

$$\min \lambda_1 C_{\text{total}} + \lambda_2 \sum_{i,j} \xi_{ij} - \lambda_3 S_{\text{total}}. \quad (4)$$

In the conclusion, the current paper emphasizes the conceptual formulation and theoretical underpinnings, the execution of this model will form the basis of subsequent empirical work. Specifically, the model will be calibrated using the detailed cost structures and consumable usage data documented across the four semesters of welding training. Historical records and expert estimates will be employed to parameterize the learning curves, while actual budget allocations will be integrated to simulate different financial scenarios. In line with standard practices in operations research, the model will be solved using both weighted-sum and epsilon-constraint techniques to generate Pareto-efficient solutions. This will allow the identification of allocation strategies that balance cost efficiency with skill achievement under realistic budget constraints. Sensitivity analyses will also be performed to examine how changes in consumable prices, trainee cohort sizes, or target competency levels affect the trade-offs. The results of these executions, including quantitative findings and policy implications, will be reported in subsequent publications.

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