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EVALUATING THE RELATIVE EFFICIENCY OF DEFENSE R&D PROJECTS IN A MULTI-PROJECT ENVIRONMENT USING EVM AND CAIV MEASURES

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Abstract. *Defense R&D projects aim to successfully develop a weapons system under time and budget constraints. Using effective project management tools is essential for achieving this goal. Certain project management tools can measure performance by integrating the technical, cost, and schedule parameters. For instance, EVM (earned value management) and CAIV (cost as an independent variable), were first applied in the defense sector. These tools provide periodically measurable and relatively comparable metrics in a multi-project environment. In this study, we present a method of evaluating the relative efficiency of multiple ongoing projects using objective data and indicators available from project management tools in weapons system development.*
Keywords: R&D project efficiency, Data envelopment analysis, EVM, CAIV

1. **Introduction.** Research & development (R&D) project-oriented organizations are required to conduct numerous projects simultaneously, resulting in the so-called multi-project environment. The main goal of individual project managers is to successfully complete the project they are responsible for within a given period and a limited budget. The R&D project director is responsible for coordinating and controlling all projects through resource re-allocation by periodically measuring their performance.

Performance evaluation can be carried out during project execution, which helps others make the right decisions in the future [14]. The most commonly cited project performance measures include cost, schedule, and technical performance outcomes [1]. Using earned value management (EVM), these three factors can be well-controlled. EVM is an effective tool for monitoring the progress and status of a project, predicting future performance, and constructing corrective action plans for getting the project back on track.

Another useful project management tool is having cost as an independent variable (CAIV). This can balance the cost, schedule, and technical performance when managing a project to a cost objective. EVM and CAIV are widely used in the US, as well as in Korea, to regularly monitor defense R&D performance and to identify the risks of ongoing projects. Some previous studies evaluated the performance (or efficiency) of R&D projects by using the performance index measured from the EVM tool. This has been performed in industry sectors; however, there are no related studies in the defense sector.

This study focuses on the efficiency analysis of defense R&D projects by using objective major indicators measured by EVM and CAIV, while considering the ongoing multi-project environment. To evaluate the relative efficiency among multi-R&D projects, the

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data envelopment analysis (DEA) method was utilized in this study, which is one of the most widely used non-parametric approaches. The DEA model can provide useful information for improving the efficiency of ineffective projects.

The remaining sections in this paper are organized as follows. Section 2 provides a background of the study and a brief review of relevant literature. Section 3 describes the proposed DEA methodology when considering the objective data and indicators. Section 4 presents a case study for evaluating the relative efficiency of multi-R&D projects. Finally, the conclusion and the extensions of this study are given in Section 5.

2. **Background and Preliminaries.**

2.1. **Project management tools.** EVM and CAIV, which are used as tools for project management in weapon system development, are described below.

Earned value (EV) is the budgeted cost of work performed (BCWP), which refers to the monetary value of the task progress actually performed during a specified period of time. The technique to manage this is called earned value management (EVM). According to the US Defense Department's EVM implementation guideline [2], EVM is a project management tool that integrates the technical, cost, and schedule parameters of a contract, and it provides significant benefits to both the government and the contractor.

In Figure 1, EVM is used to monitor a project's progress and status, and it predicts the likely future performance. From the three major indicators (BCWS, ACWP, and BCWP) of EVM, the cost and schedule variances at any point in time can be both calculated and analyzed. Additionally, from these variance measurements, the program manager (PM) can track a project's status, forecast future costs and schedule performances, and construct corrective action plans to ensure the project is on schedule or within the budget.

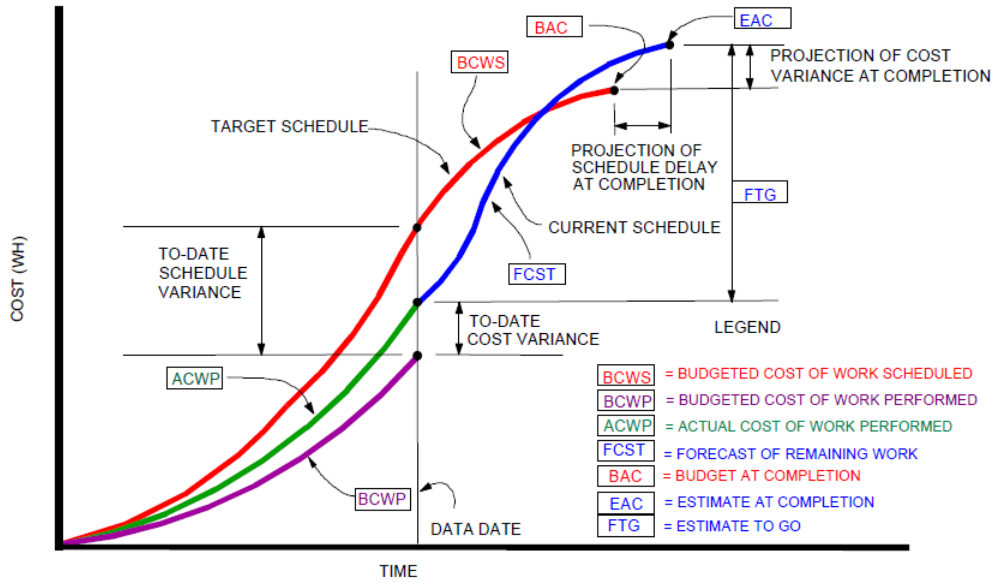

FIGURE 1. Performance measurement data elements in EVM [3]

EVM (formerly called cost/schedule control systems criteria) was developed by the US Department of Defense in the 1960s. It was adopted as a national standard or an industrial standard in the United States, Britain, and Australia. It is widely used in project management in both the industry and defense sectors.

Meanwhile, over the past three decades, defense resources were limited in many countries, and it was difficult to cover the massive cost of acquiring weapons systems, so realistic efforts were needed to reduce costs. The reduction of the weapons system acquisition cost can ultimately be achieved through repetitive weapon performance versus cost tradeoffs. This acquisition concept is CAIV, utilizing cost as an independent variable.

CAIV sets realistic and aggressive target costs (including development costs, production costs, operation & support costs) in the planning and budget phases, and periodically calculates an estimated cost during project execution to analyze and manage deviations from a predetermined target cost [4].

CAIV as an initiative to reduce defense system costs, was proposed by the US Department of Defense in 1995. It was implemented in 1996 as a part of the new 5000 Series regulations on defense system acquisitions [5], and it has been applied to all major US defense acquisition projects since 1997. In Korea, both CAIV and EVM were applied on a pilot basis to an R&D project to develop the Korean Utility Helicopter in 2006. The implementation guideline related to CAIV and EVM was enacted in 2010, and all projects with R&D expenses exceeding some level have been forced to apply CAIV and EVM.

2.2. **Data envelopment analysis (DEA).** The DEA utilized in this study is widely used to evaluate the relative efficiency of alternatives with multiple inputs and multiple outputs. DEA originated from the concept of production efficiency, proposed by Farrell in 1957 [6]. He defined production efficiency as the ratio of outputs to inputs; an alternative whose efficiency score equals 1 is called efficient. Otherwise, all other scores are inefficient in DEA approach.

Following Farrell's study, Charnes et al. in 1978 [7] introduced the term "data envelopment analysis" and proposed a DEA model (known as CCR) under the assumption of constant returns-to-scale. Later studies considered alternative sets of assumptions. Banker et al. in 1984 [8] developed a DEA model (known as BCC) under the assumption of variable returns-to-scale.

DEA's advantage is that it is a non-statistical and non-parametric method, so it can be applied even if the amount of data is relatively small, unlike the case with parametric methods. Therefore, DEA can quantitatively measure the efficiency of alternatives even if they do not have large amounts of data. Furthermore, there is no need for data normalization in the DEA model because the weights for input and output variables are realized by the model itself. The basic DEA models proposed by Charnes et al. [7] and Banker et al. [8] were formulated as a linear programming problem.

As shown in Table 1, k is the index for the alternative under evaluation (k ranges over $1, 2, \ldots, n$); j is the alternative index ($j = 1, 2, \ldots, n$); i is the input index ($i = 1, 2, \ldots, m$); r is the output index ($r = 1, 2, \ldots, s$); E_k is the efficiency score of the kth alternative; v_i is the weight given to the ith input criterion; u_r is the weight given to the rth output criterion; x_{ik} and x_{ij} are the values of the ith input criterion for the kth and jth alternatives; y_{rk} and y_{rj} are the values of the rth output criterion for the kth and jth alternatives; μ_0 is the returns-to-scale indicator; and ε is a small non-Archimedean value.

Table 1. Output-oriented DEA model (CCR and BCC)

CCR model [7]	BCC model [8]
$\text{Min } E_k = \sum_{i=1}^{m} v_i x_{ik}$ $\text{s.t. } \sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r y_{rj} \geq 0$ $j = 1, 2, \ldots, n$ $\sum_{r=1}^{s} u_r y_{rk} = 1$ $u_r, v_i \geq \varepsilon \quad \forall r, i$	$\text{Min } E_k = \sum_{i=1}^{m} v_i x_{ik} + \mu_0$ $\text{s.t. } \sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r y_{rj} + \mu_0 \geq 0$ $j = 1, 2, \ldots, n$ $\sum_{r=1}^{s} u_r y_{rk} = 1$ $u_r, v_i \geq \varepsilon \quad \forall r, i$

2.3. **Review of previous studies.** Several studies [9-11] have been conducted to e-valuate the performance of core technology projects, which are required before weapons system development. These studies only analyzed completed projects, and the input and output criteria were very similar as shown in Table 2. The input criteria considered for R&D, were investment costs, number of employees, and project duration. The output criteria included papers published in journals, the number of patents granted, and products resulting from the developed technology.

Table 2. Comparison of previous studies on efficiency analysis of R&D projects

Paper	DEA model	Inputs	Outputs
Park and Na [9]	output-oriented CCR, BCC	investments, employees	patents, products
Lee and Chung [10]	output-oriented CCR	investments, employees	papers, patents, products
Lim and Jeon [11]	output-oriented BCC	investments, employees, duration	papers, patents, prototypes
Tohumcu and Karasakal [12]	DEA with AR constraints	cost/schedule deviation, risk handling, etc.	contribution to self-development, supplementary payment
Vitner et al. [13]	DEA	cost, work content, level of monitoring	design/operations yield, CPI, SPI
Azimian et al. [14]	output-oriented BCC	actual cost, importance coefficient	income, quality coefficient, CPI, SPI

Tohumcu and Karasakal [12] evaluated the performance of ongoing R&D projects in a defense R&D institute. By using a super-efficiency CCR model with the assurance region (AR) constraints obtained from the analytic network process method, the discriminatory power of DEA increased.

The efficiency analysis of R&D projects using the cost performance index (CPI) and the schedule performance index (SPI) measured from the EVM tool was performed in the industry sector [13,14]. Vitner et al. [13] applied the DEA method for assessing relative efficiency in a multi-project environment. By integrating the EVM system and the multi-dimensional control system (MDCS), they attempted to define objective criteria for project comparisons, such as SPI, CPI, design yield, and operations yield.

Azimian et al. [14] demonstrated the DEA usage for the sensitivity analysis of efficiency projects in industry applications. They used EVM indexes, such as actual cost, CPI, and SPI, for considering identical input and output criteria for projects. The comparison of the reviewed papers is summarized in Table 2.

3. **Proposed Methodology.** To use a DEA model as an efficiency evaluation method for ongoing multi-R&D projects, reference the proposed procedure in Figure 2, which will be applied to the case study described in Section 4. Each step of this procedure is described in detail in this section and next section.

3.1. **Definition of inputs and outputs.** Previous studies [9-11] included the number of papers, patents, and products as output criteria for the post-evaluation of completed R&D projects. Since this study will compare the relative efficiency of ongoing R&D projects, the inputs, as well as outputs, should be different from those used in previous studies. In this study, the objective data and indicators that can be obtained from EVM and CAIV tools are considered inputs and outputs. However, subjective criteria are not considered for evaluating the periodic (e.g., monthly, quarterly) efficiency of ongoing R&D projects.

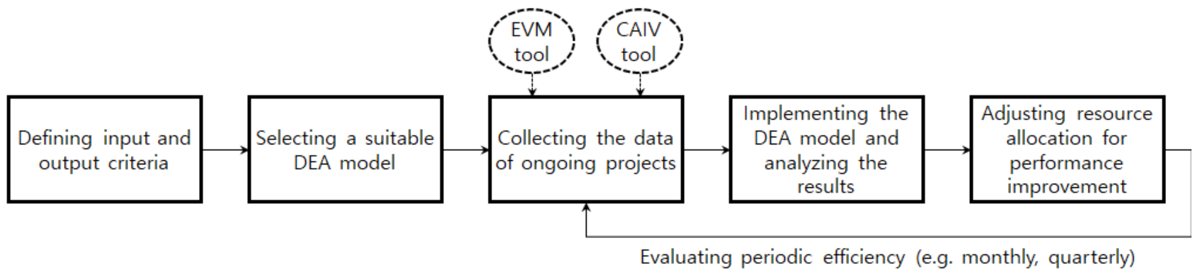

Figure 2. Proposed procedure for this study

Based on our own experiences and on findings from previous studies [13,14], we selected two inputs (ACWP, AMH), and three outputs (CPI, SPI, DET) for a DEA analysis. The definitions of each input and output are described in detail below.

- ACWP (costs): is the actual cost of work performed and is defined as the actual amount of expenses used to complete work of a project during a certain period of time.
- AMH (hours): is the actual man-hours and is defined as the actual amount of labor used to complete the work of a project during a certain period of time.
- CPI (index): is the cost performance index and is defined as the budgeted cost of work performed (BCWP) divided by the actual cost of work performed (ACWP); CPI < 1 (over budget), CPI $= 1$ (exactly on budget), CPI > 1 (under budget).
- SPI (index): is the schedule performance index and is defined as the budgeted cost of work performed (BCWP) divided by the budgeted cost of work scheduled (BCWS); SPI < 1 (behind schedule), SPI $= 1$ (exactly on schedule), SPI > 1 (ahead of schedule).
- DET (%): is the difference of the target versus the estimated cost and is defined as the percentage of target production unit cost divided by the estimated production unit cost; DET < 100 (over target), DET $= 100$ (exactly on target), DET > 100 (under target).

3.2. **Selection of a DEA model.** The most important goal of a project manager in weapon system development is to successfully complete development within a given period and within a limited budget. This means maximizing outputs rather than reducing inputs to improve project efficiency, and also, it cannot be assumed the returns-to-scale of R&D activities is constant.

Therefore, an output-oriented BCC model with variable returns-to-scale [8] is applied to evaluating the relative efficiency in this study. To obtain useful information for improving efficiency, as well as to reduce its constraints, the original BCC model in Table 1 is transformed into a dual problem model in Equation (1):

$$
\begin{aligned}
\text{Max} \quad & E_k = \theta + \varepsilon \left[\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+ \right] \\
\text{s.t.} \quad & -\sum_{j=1}^{n} \lambda_j y_{rj} + \theta y_{rk} + s_i^+ = 0 \quad r = 1, 2, \ldots, s \\
& \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = x_{ik} \quad i = 1, 2, \ldots, m \\
& \sum_{j=1}^{n} \lambda_j = 1 \\
& s_i^-, s_r^+, \lambda_j \geq 0 \quad \forall i, r, j
\end{aligned}
\tag{1}
$$

4. Case Study.

4.1. Data collection. In this section, we apply the proposed methodology for evaluating the relative efficiency among a set of R&D projects for weapons systems. The data set in this case study was taken from an anonymous R&D organization, as shown in Table 3. The case study covers fifteen ongoing R&D projects using both EVM and CAIV. Two inputs (ACWP, AMH) and two outputs (CPI, SPI) are the data and the indicators obtained from the EVM tool, while the other one output (DET) was obtained from the CAIV tool.

Table 3. Input and output descriptive statistics for fifteen R&D prjects

Statistics	Inputs		Outputs		
	ACWP (costs)	AMH (hours)	CPI (index)	SPI (index)	DET (%)
Mean	149.49	62,491	0.85	0.95	94.07
Std. dev.	74.62	33,294	0.11	0.10	14.78
Minimum	49.49	18,376	0.66	0.65	67.09
Maximum	303.98	142,863	0.97	1.07	122.19

4.2. Results analysis. Based on the above data set, Tables 4 and 5 report the final results for this case study using the output-oriented DEA-BCC model. In the output-oriented DEA model, the efficiency score of the efficient alternative is equal to 1, while the efficiency score of the inefficient alternative is greater than 1.

In Table 4, eight of the fifteen ongoing R&D projects are efficient and the remaining seven are relatively inefficient. It provides the reference set, which can be used as a benchmark for improving inefficient projects. Projects 1, 2, and 12, which appear in many reference sets, are not only efficient, but also robust in this case.

Table 4. Results of the relative efficiency analysis for fifteen R&D projects

Projects	Efficiency	Reference set	Projects	Efficiency	Reference set
P1	1.000		P9	1.000	
P2	1.000		P10	1.100	{P12}
P3	1.056	{P1, P2, P14}	P11	1.205	{P1, P9, P12, P15}
P4	1.013	{P1, P12}	P12	1.000	
P5	1.024	{P1, P2, P9}	P13	1.000	
P6	1.058	{P2, P12, P13}	P14	1.000	
P7	1.000		P15	1.000	
P8	1.029	{P2, P14}	Mean	1.032	

Table 5. Target values for improving the inputs and outputs of inefficient projects

Projects	ACWP (costs)	AMH (hours)	CPI (index)	SPI (index)	DET (%)
P3	N/A	−11,176 (16.6%)	0.05 (5.6%)	0.05 (5.6%)	13.39 (15.7%)
P4	−118.89 (39.1%)	−63,373 (44.4%)	0.13 (17.3%)	0.01 (1.3%)	1.28 (1.3%)
P5	N/A	−9,024 (17.7%)	0.02 (2.4%)	0.02 (2.4%)	6.70 (7.4%)
P6	−8.77 (6.6%)	N/A	0.05 (5.8%)	0.07 (8.3%)	6.01 (5.8%)
P8	−32.95 (15.8%)	N/A	0.03 (2.9%)	0.05 (5.8%)	31.09 (46.3%)
P10	−121.66 (56.7%)	−65,479 (63.7%)	0.12 (16.8%)	0.35 (53.5%)	11.08 (10.0%)
P11	N/A	N/A	0.14 (21.1%)	0.17 (20.5%)	17.76 (20.5%)

After evaluating the relative efficiency among R&D projects, one of the results that may be interesting to the project director is information about the quantitative improvement targets of inefficient projects, which can be obtained through the DEA projection analysis. Using this information, he or she can construct corrective action plans, such as resource re-allocation, to make an inefficient project efficient, if necessary.

The projected target values presented in Table 5 show how the inputs and outputs of inefficient projects can be adjusted for them to move towards an efficient frontier. In Table 5, all inefficient projects were determined to need increases for CPI, SPI, and DET. For example, project 3 needs to decrease AMH by 16.6%, while increasing CPI, SPI, and DET by 5.6%, 5.6%, 15.7%, respectively.

In this multi-project environment, it is recommended that an ongoing project's efficiency analysis be performed regularly (e.g., monthly, quarterly). This is possible because our proposed methodology uses objective data and indicators, which can be easily obtained from EVM and CAIV tools without considering subjective criteria. If a new project started or if an ongoing project completed, an efficiency assessment needs to be performed by updating the project analysis list.

5. **Conclusion.** In this study, we presented a method of evaluating the relative efficiency in multiple ongoing projects using objective data and indicators that were obtained from scientific project management tools applied in the defense sector. The efficiency analysis used the output-oriented DEA-BCC model because of its R&D characteristics. Additionally, it was converted to a dual problem, which obtained useful information for improving the efficiency of inefficient projects.

Future research can be extended to this case by using additional indicators available from other project management tools. In this case, when input or output criteria are added, it will be necessary to apply a DEA method, with the assurance region (AR) constraints, to increase the discrimination power of the traditional DEA model.

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