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# Robust Optimization Model for R&D Project Selection under Uncertainty in the Automobile Industry

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**Abstract:** In a company, project management is responsible for project selection from candidates under some limited constraints to achieve the company's goal before the project begins as well as the project operations in progress. The development of new technologies and products can broaden a company's market share, and to do so, research and development (R&D) projects are significant. However, limited funds force a company to select projects that can best represent the company's interests. As projects may take a long time to develop, a number of uncertainties may occur, and the most concerning uncertainty is cost uncertainty. In this study, a robust optimization decision model for project selection considering cost uncertainty is proposed to assist the decision-making process for companies that need to select projects from a number of candidates due to limited funds. The model considers project selection in view of the total cost of ownership, which is a key factor for customers and companies in the automobile industry. The proposed model is tested in the automobile industry environment with different conservatism levels about cost uncertainty, and an analysis of expected market changes and a company's income is performed with the solutions obtained from the proposed model. The result shows that the presented model reacts to cost uncertainty robustly for assisting the decision-makers in the company.

**Keywords:** robust optimization; project selection; total cost of ownership; project management; automobile; sustainable development

## 1. Introduction

The term "sustainability" is derived from sustainable development, which is a holistic approach that includes social, economic, and environmental perspectives [1]. The concept of sustainability has been employed by many industries to increase sustainability and extend it to diverse domains.

In particular, sustainability is considered a critical factor in the automobile industry due to the characteristics of the industry. Recent trends in the automobile industry demonstrate that automobile manufacturers are interested in developing hydrogen as a fuel source as well as eco-friendly electric vehicles. Furthermore, European emission standards (EURO), which regulate the toxic emissions of vehicles such as cars, trucks and buses are becoming stricter. Since EURO 6 was implemented in 2015, automobile manufacturers have increasingly regarded sustainability as a primary issue.

Achieving sustainability has emerged as an important issue and is regarded as a challenging goal for companies [2]. As global competition intensifies, companies that are dependent on innovation to stay in business focus on developing new products to maintain or increase their competitiveness in the market. Research and development (R&D) is a foundational activity within these companies because it is necessary to create new products or upgrade existing products by developing new technologies. Companies need to make a profit, and they also operate with limited resources and funds. Because new products generate profit and are based on the R&D projects that are selected to be funded using limited operating funds, R&D project selection is an important component of companies' decision-making processes. R&D activities are especially important to automobile manufacturers. R&D projects develop new technologies that are then incorporated into new cars, and these new technologies directly affect profits because they have an impact on customers' responses in the market. As mentioned above, the automobile industry is closely affected by environmental regulations. Therefore, automobile companies need to consider sustainability when developing new vehicles, which is the beginning of the process of R&D project selection.

When selecting R&D projects, multiple criteria and expert opinions are considered, and the conflicts between stakeholders and departments must be reconciled [3]. In recent years, a variety of R&D project selection models have been developed that utilize various techniques, such as economic models, mathematical programming, etc., to select appropriate projects [4]. An analytic network process (ANP) is a multi-attribute approach that transforms qualitative values into quantitative ones. This is a simple and intuitive method that can be accepted by decision-makers. Meade and Presley [2] addressed the problem of R&D project selection with ANP. In another approach, the analytic hierarchy process (AHP), complex decisions are expressed in a hierarchical structure with criteria for the evaluation of activities. Liberatore [5] developed the AHP modeling framework for R&D project selection, and the AHP was used to allocate resources and determine priorities for R&D projects.

Other approaches to R&D project selection include fuzzy numbers and the technique of order preference similarity to the ideal solution (TOPSIS). Kuchta [6] assumed a fuzzy number for the net present value of each R&D project and presented a project selection model. The TOPSIS is a technique that selects a solution with the shortest distance from a positive ideal solution and the longest distance from a negative ideal solution. Amiri [7] used a new method that included TOPSIS, fuzzy numbers, and AHP, and provided a method to evaluate alternative projects to select the best one. In addition, data envelopment analysis (DEA) [8] and balanced scorecard (BSC) [9] have also been used to select R&D projects.

Recently, artificial intelligence (AI) has emerged and has been applied in diverse fields [10,11]. In the project management field, Razi and Shariat [12] used a neural network to rank projects that were classified by the decision tree algorithm. The classes were analyzed by grey relational analysis. Another study utilized AI methods to predict the duration of products, and the methods were compared with earned value management and earned schedule methods [13].

Various techniques have been adapted for R&D project selection. However, the uncertainty of projects must be considered due to the nature of R&D projects, such as the long planning and development period.

There have been many different approaches to deal with R&D project uncertainty in project selection. For example, Carlsson et al. [14] developed a fuzzy real options model to handle the uncertainty of R&D projects. In addition, Modarres and Hassanzadeh [15] developed a model to consider uncertainty that is due to unreliable or unavailable data in R&D project selection, with real option valuation to maximize the expected benefits.

This study, a robust optimization model (ROM), which is based on the model developed by Lee et al. [16], is presented for R&D project selection that considers the uncertainty of R&D projects in the automobile industry. This model incorporates sales and revenue models that consider the total cost of ownership (TCO) of a commercial vehicle. TCO is defined as the total cost of owning a period of a product. In the commercial vehicle market, business customers purchase vehicles to transport cargo. Hence, customers regard the cost of operating the vehicles for a period of ownership as well as the purchase cost and even the salvage value as important factors when purchasing the vehicles. Therefore, when developing new vehicles, project portfolio selection impacts the increasing purchase cost and the decreasing maintenance cost due to the efficiency of the selected projects. In these models, the uncertainty of R&D projects was excluded as well as the total budget limitations. Therefore, R&D projects are selected using the robust optimization model presented in this study, which considers the uncertainty of R&D projects and total budget limitations, and sales and revenue generated from the selected R&D projects are computed by their models. Using this framework, R&D project selection becomes more practical for automobile companies, and it is possible to engage in sustainable project management from a managerial perspective.

The remainder of this paper is organized as follows. Section 2 discusses the literature review. In Section 3, the ROM for R&D project selection is discussed, in addition to the TCO model and the sales function. Section 4 presents the empirical experiment for the ROM using the TCO of a commercial vehicle. In addition, it includes an analysis of sales in the market and revenue, based on robust optimization solutions determined through the ROM. Sections 5 and 6 address the discussion and conclusions, respectively.

## 2. Literature Review

### *2.1. Sustainable Development in Automobile Industry*

Sustainable development is one of the main concerns for automobile companies considering carbon emission and other pollutions as critical issues [17]. The automobile market has been growing throughout the world including America and Europe as the demand for automobiles has kept increasing. Automobile manufacturers have a high return, which they seek ways to maintain, and increase their sales in the market. However, manufacturers face some challenges such as government regulations related to sustainable development and high competitiveness in the market [18]. EURO has been getting stricter for automobile manufacturers, and they are required to control the carbon emission of vehicles. The EURO was introduced by the European Union (EU) in 1990 to regulate automobile carbon emissions. EURO 1 started in 1992, and today, EURO 6 has applied since 2015. For EURO 6, the nitrogen oxide ($NO_x$) and particular matter (PM) are regulated more strictly than the previous EURO. This standard is critical for automobile manufacturers because they have to pay a huge fine and cannot sell vehicles if they do not follow the regulations. Therefore, automobile manufacturers changed the design of the vehicle engine to comply with the regulations. As such, regulations are anticipated to be applied more strictly to the automobile industry; manufacturers have been developing a smart vehicle control system to improve fuel efficiency. One of the technologies for a smart control system is the idle-stop-and-go (ISG), and the recent trend suggests that vehicles must be equipped with an ISG system. The ISG system turns off the engine when a vehicle is stopped and runs the engine when a vehicle runs again, which helps reduce fuel consumption when the vehicle idles. Although traditional fossil fuel is used, the ISG system improves fuel efficiency, which is one of the ways to protect the environment.

Thus, automobile manufacturers are facing pressure in terms of reducing the costs incurred as a result of the tightened environmental regulations, and they are investing more and more into R&D to develop technologies that can address the environmentally friendly and sustainability requirements. This will lead to increased competitiveness for surviving in the automobile market, and the role of project management for R&D becomes more significant at the same time.

### *2.2. Project Management*

Project management is the planning and monitoring of projects so the objective of the projects can be achieved in a timely manner while considering cost, quality, and performance [19]. Sanchez and Terlizzi [20] suggested a new measure for project management that considered multiple factors analysis using hierarchical models, as the projects were completed within the specified cost and time. Tran and Long [21] developed a multi-objective optimization model for project scheduling and presented an algorithm that considered time, cost, and risk at the same time. Mahmoudi and Feylizadeh [22] proposed an integer programming model to minimize the cost of a project that focused on project crashing in consideration of cost, time, quality, and risk.

Recently, project management has been addressed from the perspective of sustainability. Kivilä et al. [23] identified the control practices used for sustainable project management, and a case study was conducted on a large infrastructure project. By analyzing a survey completed by project managers, Martens and Carvalho [24] suggested four factors that affected project management: economic and competitive advantage, sustainable innovation business model, environmental policies and resource-saving, and stakeholder management.

Project management broadens the goals of realizing a successful project to match a company's strategic goals. However, if goals are successfully achieved for maximizing stakeholders' value while balancing resource allocation and risk, project selection is the main factor for project success. Thus, the process of project selection occupies a considerable significance for strategic business [25]. However, project selection is complex due to many factors: interrelationships between projects, uncertainty, changes over time, and success factors that are difficult to measure [26].

Among the diverse factors, uncertainty is a critical matter for a company because it leads to risk for the company. In particular, cost uncertainty is one of the most direct factors affecting the operations of a company. Therefore, in this study, cost uncertainty and project efficiency are considered for project selection.

### *2.3. Robust Optimization*

Robust optimization has been studied and applied in many management fields, such as supply chain, portfolio selection, and the health care system [27]. Bertsimas and Thiele [28,29] made use of robust optimization in the supply chain management and inventory field. Hassanzadeh et al. [30] presented an interactive robust weighted Tchebycheff procedure to suggest robust solutions to the R&D project portfolio selection problem. The solutions from this study suggested that they have a high feasibility percentage.

Soyster [31] addressed the concept of uncertainty with a linear programming problem with uncertainty. His approach to robust optimization results in a solution that was feasible in a convex set. Starting from Soyster [31], robust optimization has been developed to consider ellipsoidal uncertainty and to solve over-conservatism issues [32–38]. To address the issues and reduce the level of conservatism, the robust counterparts in conic quadratic problems were involved. Even though ellipsoidal uncertainties can be used to solve more complicated uncertainty sets, this approach was less practical because it led to nonlinearity. Bertsimas and Sim [39,40] presented an alternative approach that took advantage of the linear rather than quadratic and can control the level of conservatism.

This study uses the robust optimization approach proposed by Bertsimas and Sim [39] for R&D project selection. As robust optimization considers uncertainty, the model includes the cost uncertainty of projects in the automobile industry. In reality, uncertainty is a critical factor affecting R&D project selection, which affects a company's future if the anticipated results are completely different from what is originally proposed. The model assists decision-makers in considering the control of conservatism levels in terms of uncertainty when selecting an R&D project. In the model, the TCO is considered because the TCO is an important factor for customers and automobile manufacturers. The customers who operate their business with vehicles are interested in vehicles with low TCO when they purchase them because of the low cost. In addition, automobile manufacturers can attract customers in the market with vehicles having a low TCO. The TCO is suitable to incorporate the perspective of sustainability as the TCO includes the whole lifespan of a product and its end-of-life cost [41].

### *2.4. Total Cost of Ownership*

TCO has been applied in a variety of fields and addressed by many researchers. In the supplier selection field, TCO is a purchasing tool that determines the cost of buying a product or service from suppliers [42] as the supplier selection process is an important factor that affects the market competitiveness of manufacturing companies. Kanagaraj et al. [43] approached the supplier selection problem by examining all costs from the perspective of reliability-based TCO. They argued that the minimum TCO was achieved when the supplier selection was made using their model. Dogan and Aydin [44] combined Bayesian networks and TCO to analyze the supplier selection process, in which the target was to use and incorporate the information that the buyer had about the uncertainty of the suppliers. Degraeve et al. [45] proposed using the TCO concept for evaluating vendor selection and mathematical programming models based on TCO. The models outperformed the rating models for a specific case with real data. Wouters et al. [46] investigated utilizing the concept of TCO to enhance supplier decisions because TCO assisted purchasing decision-makers. Eight factors were selected and used to develop a model to explain TCO.

Another field that exploits TCO is the automobile industry, and many studies have been conducted regarding TCO in this industry. The concept of TCO is very useful and is a critical factor for both customers and manufacturers. Using TCO, customers are able to calculate the total cost when they purchase a car. Thus, with the estimation, they can evaluate which car is a good fit for their life or business. Manufacturers attract customers with low TCO, which can help increase sales and revenue. Sutcu [47] proposed a decision-making model incorporating approximation methods that utilize cumulative residual entropy. The decision-making model assists customers in determining which costs are affordable for them when purchasing a sedan. Palmer et al. [48] exploited TCO for hybrid and electric vehicles and compared the market shares of different countries. Investigating the TCO of conventional, hybrid, plug-in hybrid, and battery electric vehicles in three countries, the relationship between the TCO of hybrid electric vehicles and their market share was analyzed based on a panel regression model. Letmathe and Suares [49] calculated the TCO for battery electric vehicles and hybrid electric vehicles and compared these with internal combustion engine vehicles in the German market. The analysis showed the cost-efficiency of vehicles considering subsidies, distances, and brands. Lee et al. [16] proposed the TCO model for a commercial vehicle and considered the model to be a project selection problem by suggesting the sales function. The function was non-linear so that the enumeration method was employed to solve the project selection problem with the sales function.

In this study, the presented ROM adapts the TCO proposed by Lee et al. [16], and the sensitivity analysis is performed with solutions from the model, based on the sales function proposed by Lee et al. [16] in the perspective of the expected sales and revenue affected by the selected projects.

## 3. Robust Optimization Model for R&D Project Selection

The goal of this study is to propose a robust optimization model (ROM) for R&D project selection in the automobile industry to address the cost uncertainty of projects, as cost uncertainty can lead to risk for the company.

The ROM considers the TCO, which is one of the important factors for customers and companies. This is especially true when customers operate their vehicle for business, because the TCO is related to their profits.

Before presenting the ROM, the TCO model is explained as is the interrelationship between TCO, the projects, and the sales function is explained. The TCO model and the sales function, developed by Lee et al. [16], are employed.

### 3.1. TCO Model and Sales Function

The definition of $TCO$ is the total cost of a product for the period of ownership. The basic concept is that the $TCO$ consists of the purchase cost ($PC$), maintenance cost ($MC$), and salvage value ($SV$) of a product [16]. Supposing that the product is comprised of several items, let $j$ be an item that is required for replacement yearly and then $\sum_j MC_j$ is defined as the total maintenance cost for a year. In the case of $SV$, the product value after the ownership period $OP$ is described as, $(1 - f(OP)) \times PC$ where $f(OP)$

is the depreciation rate for *OP*. In view of the cost of *OP*, the equation for the *TCO* model is described below, and Table 1. shows the notations used in the *TCO* model.

$$TCO = PC + OP \cdot \sum_j MC_j - SV = PC \cdot f(OP) + OP \cdot \sum_j MC_j \quad (1)$$

**Table 1.** Notations used in Total Cost of Ownership (TCO).

| Notation | Description |
| --- | --- |
| $j$ | An item consisting of a product that needs to be replaced regularly |
| $OP$ | Ownership period |
| $f(OP)$ | Depreciation rate for $OP$ |
| $PC$ | Purchase price of product |
| $MC_j$ | Maintenance cost (MC) of item j of product |
| $SV$ | Salvage value |

In the case of an R&D project, the goal can be to enhance the durability or performance of the product, and the product is upgraded by applying technologies developed by the project. From this point of view, the project affects *PC*, *MC*, and *SV*. For example, the cost of a project can increase the *PC* of the product, and the efficiency of the project can decrease the *MC* because of the improved durability of the items that constitute the product. In addition, both new *PC* and new *MC* can directly and indirectly influence the depreciation rate of a product, which calculates the *SV*. For example, if a new product with proper *PC* and *MC* is developed by the projects and highly rated by customers in the market, the value of the product in the market can be increased and the *SV* of the product can be high, which lowers its depreciation rate. In other words, the projects can affect the costs of the product, and thus *TCO* is affected by R&D projects.

In the project selection problem, let $k$ be the project and $x_k$ a decision variable for the project $k$. For the project $k$ attributes, $F_k$ is the cost of the project $k$ and $e_{jk}$ denotes the efficiency of the project $k$ on item $j$ in MC. Therefore, $\sum_k c_k x_k$ is equivalent to the total cost for a company and $\sum_k e_{jk} x_k$ is the total efficiency of the total selected projects on item $j$ of the MC. Assuming that the efficiency factor impacts a percentage (%), $\sum_k e_{jk} x_k$ follows a certain function $g(\cdot)$, which can be described as $g\left(\sum_k e_{jk} x_k\right)(\%)$, and $\sum_j MC_j\left(1 - g\left(\sum_k e_{jk} x_k\right)\right)$ is equivalent to the new *MC* reduced by the projects from the *MC*.

The sales function is derived from the idea that the variation in *PC* and *MC* due to projects affects customers' purchasing opinions. For example, the total cost for a company, $\sum_k c_k x_k$, reflects the *PC* that may be increased. In addition, a lower *MC*, $\sum_j MC_j\left(1 - g\left(\sum_k e_{jk} x_k\right)\right)$ than before can attract customers in the market. Equation (2) shows the sales function proposed by Lee et al. [16]. Table 2. shows the notations for the project and sales function, and a detailed explanation for the sales function is described in [16].

$$n \cdot \sum_j MC_j \cdot PC \cdot y^2 - n \cdot y_0 \cdot \beta_1 \left(\sum_j MC_j \cdot g\left(\sum_k e_{kj} x_k\right)\right) \cdot PC \cdot y + \alpha \cdot \beta_2 \cdot y_0 \left(\sum_k c_k x_k\right) \cdot \sum_j MC_j = 0 \quad (2)$$

**Table 2.** Notations for the project and sales function.

| Notation | Description |
|---|---|
| $k$ | Project $(k = 1, \ldots, K)$ |
| $e_{jk}$ | Efficiency factor for $MC$ of item $j$ for a product by project $k$ |
| $c_k$ | Cost of project $k$ |
| $g(\cdot)$ | Certain function |
| $x_k$ | Decision variable of project $k$ |
| $y$ | Expected sales volume in the market |
| $y_0$ | Previous sales volume in the market |
| $n$ | Sales period plan for a product in consideration |
| $\beta_1$ | Advantageous rate of sales increase due to $MC$ decrease |
| $\beta_2$ | Disadvantageous rate of sales increase due to $PC$ decrease |
| $\alpha$ | PC increase factor due to the unit investment for product |

### 3.2. Robust Optimization Model

In this study, the ROM for R&D project selection is proposed considering factors related to the TCO. In this model, the main decision-making is to select projects from a number of candidate projects within the limited budget for maximizing the cost reduction of the $MC$ in consideration of the cost uncertainty of projects.

Robust optimization is a technique to find the optimal solution in a problem with inherent uncertainty. Many optimization problems use uncertain data, and the data are random, or are often difficult to estimate mathematically due to environmental changes or lack of knowledge about parameters. The robust optimization technique is used under the basic assumption that even when the probability distribution of data is difficult to know, all data are realized within a specific uncertainty set. In other words, by using a robust optimization technique, even if users do not know the exact probability distribution of the data and it assumes to realize the data in a range in advance (empirically), the robust solution can be obtained in realizing all data in a range.

As mentioned earlier, the uncertainty of the cost of projects is considered and expressed in intervals. Because a company operates with limited funds, the uncertainty of the cost can be a risk when investing in R&D projects because the success of products upgraded by the projects in the market cannot be assured. Therefore, it is critical for a company to consider the uncertainty of project costs.

Assuming that $c_k$ is the nominal value of the cost of the project $k$, the exact value $\widetilde{c_k}$ is unknown and is in the interval $[c_k - \hat{c}_k, c_k + \hat{c}_k]$ where $\hat{c}_k$ is the half-interval width of $c_k$. The significant characteristic of the ROM is $\Gamma$, which is the adjustment of the robustness against the level of conservatism of the solution. The absolute value of the scaled deviation of the uncertainty of $\widetilde{c_k}$ from $c_k$ is defined as follows:

$$\pi_k = \left| \frac{\widetilde{c_k} - c_k}{\hat{c}_k} \right|, \ \forall k \tag{3}$$

The interval of $\pi_k$ is in the range [0, 1], and $\Gamma$ for the cost uncertainty of the projects is defined as follows:

$$\sum_{k=1}^{K} \pi_k \leq \Gamma \tag{4}$$

where Γ is in the range [0, K], and $\Gamma = 0$ and $\Gamma = K$ correspond to the nominal case and the worst case, respectively The ROM is presented below, and Table 3 shows the notations for ROM.

$$\begin{gathered} Max\ \sum_j MC_j \cdot \sum_k e_{jk} \cdot x_k \\ Subject\ to \\ \sum_k c_k x_k + \max_H \left\{ \sum_{k \in S} \hat{c}_k |x_k| + (\Gamma - [\Gamma]) \hat{c}_q \left| x_q \right| \right\} \le B \\ x_k \in \{0,1\} \end{gathered} \tag{5}$$

**Table 3.** Notations for robust optimization model.

| Notation | Description |
|---|---|
| $B$ | Total budget |
| $\hat{c}_k$ | Value of interval for $c_k$ |
| $\widetilde{c_k}$ | Value in $[c_k - \hat{c}_k, c_k + \hat{c}_k\ ]$ |
| $G = \{k \mid \hat{c}_k > 0\}$ | Set of projects having cost uncertainty |
| $\Gamma \in [0, \lvert G \rvert]$ | Interval of conservatism level of cost |
| $H$ | Subset of $G$, $H = \{S \cup \{q\} \big\| S \subseteq G, \lvert S \rvert = [\Gamma], q \in G \backslash S\}$ |

The objective is to maximize the amount of *MC* that will be reduced by the projects. The constraint is a budget limitation considering the cost uncertainty of projects.

Since the model described above is nonlinear, the model is reformulated as a linear optimization model (6).

$$\begin{gathered} Max\ \sum_j MC_j \cdot \sum_k e_{jk} \cdot x_k \\ Subject\ to \\ \sum_k c_k x_k + z \cdot \Gamma + \ \sum_k p_k \le B \\ z + p_k \ge \hat{c}_k y_k,\ \forall\ k \\ -y_k \le x_k \le y_k,\ \forall\ k \\ x_k \in \{0,1\} \\ z,\ y_k,\ p_k \ge 0 \end{gathered} \tag{6}$$

The detailed transforming formulation from a nonlinear model to a linear model is explained in [39]. Figure 1 shows the relation between the project selection model, the TCO of a product, and the sales in the market.

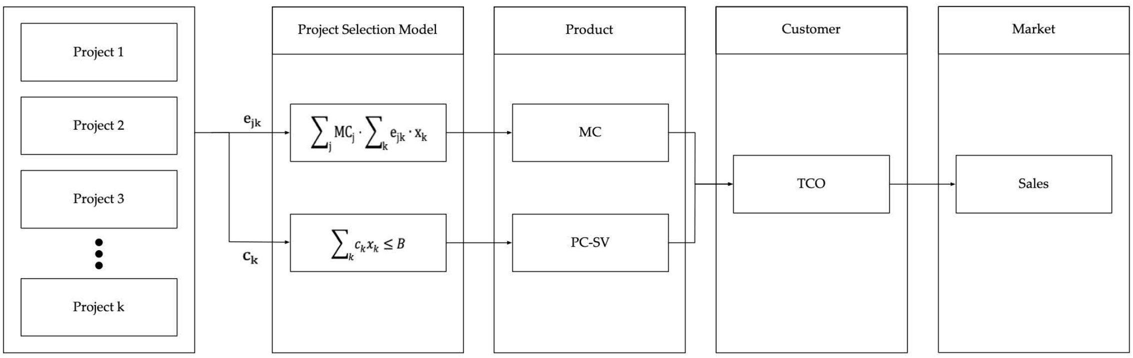


**Figure 1.** The relation between the project selection model, the TCO of a product, and the sales in the market.

## 4. Empirical Experiment

In this section, the proposed ROM is tested using diverse cases, and the data used for the ROM are adopted from [16]. The ROM was coded in the Java language and tested on a 3.20 GHz Intel-core i7 with 16 GB of memory. As a product of the TCO, a commercial vehicle was selected because customers who purchase this vehicle are sensitive to its cost. They use the vehicle for transporting cargo, so the *MC* is very critical for their profit. The detailed data for the TCO of this vehicle are described in [16].

The project attribute data provided in [16] was used, and cost uncertainty was added in this study. Uncertainty was categorized as low, middle, or high and generated randomly within a certain range. Low uncertainty was generated in the range of [10–30], middle in the range of [40–60], and high in the range of [70–90]. Table 4 shows the project attribute data used in this study.

**Table 4.** Project attribute data.

| Project $k$ | $c_k$($10^4$) | $e_{k1}$ (%) | $e_{k2}$ (%) | $e_{k3}$ (%) | Cost Uncertainty (%) | | |
|---|---|---|---|---|---|---|---|
| | | | | | Low | Middle | High |
| 1 | 650 | 2 | 1 | 0.5 | 30 | 40 | 70 |
| 2 | 2540 | 1.5 | 1 | 1.5 | 20 | 60 | 80 |
| 3 | 1785 | 1 | 1.5 | 2 | 30 | 60 | 70 |
| 4 | 930 | 3 | 2.5 | 1 | 10 | 60 | 70 |
| 5 | 1705 | 1 | 2.5 | 1.5 | 30 | 40 | 70 |
| 6 | 895 | 4 | 1 | 2 | 10 | 40 | 80 |
| 7 | 2290 | 1.5 | 1.5 | 0 | 20 | 50 | 70 |
| 8 | 1555 | 1 | 2 | 2.5 | 10 | 60 | 80 |
| 9 | 1890 | 0.5 | 2 | 2.5 | 20 | 40 | 90 |
| 10 | 735 | 0.5 | 2.5 | 1.5 | 20 | 50 | 90 |
| 11 | 1060 | 1 | 2.5 | 0 | 30 | 50 | 90 |
| 12 | 1250 | 1.5 | 1.5 | 2 | 20 | 50 | 70 |
| 13 | 1200 | 2.5 | 0 | 2.5 | 10 | 40 | 90 |
| 14 | 845 | 2.5 | 0 | 1.5 | 30 | 40 | 90 |
| 15 | 1135 | 0 | 1.5 | 0 | 20 | 60 | 80 |
| 16 | 1700 | 1.5 | 1.5 | 1.5 | 20 | 50 | 70 |
| 17 | 625 | 2 | 2.5 | 0 | 10 | 40 | 80 |
| 18 | 500 | 0 | 1.5 | 0 | 10 | 60 | 90 |
| 19 | 2115 | 2.5 | 2 | 2.5 | 30 | 60 | 90 |
| 20 | 1200 | 2.5 | 2.5 | 2.5 | 20 | 60 | 90 |

Assuming that there are R&D projects to be selected within the limited budget of a company, the total budget is divided into three parts for testing the ROM: small, medium, and large. The small, middle, and large budgets are $30 million, $50 million, and $100 million, respectively. As the uncertainty is expressed as a percentage, $\hat{c}_k$ is calculated using the uncertainty and $c_k$. For example, in the low uncertainty case, the interval of the cost of project 1, $\hat{c}_1$, is 19.5. The critical ROM is $\Gamma$, which represents the control of the conservatism level. As mentioned above, when $\Gamma$ is 0, it is a nominal case in which the uncertainty is not reflected, and Table 5 shows the result of the ROM for each budget case without uncertainty. As shown in Table 5, projects 4 and 6 were selected in all cases because these were cost-effective without considering the uncertainty. Figure 2 shows the reduction in the *MC* by the selected projects according to different values of $\Gamma$ in a range of [0, 20] in two uncertainty cases and three total budget cases. In the low uncertainty case, the variation of the objective value in accordance with the values of $\Gamma$ was slight. As seen in Figure 2, the objective value decreased when the conservatism level increased for the uncertainty. However, after reaching a certain level, the objective value remained constant and did not decline further. In addition, when the uncertainty was higher, the decreasing effect of the objective value was larger.

**Table 5.** Results of ROM with a limited budget for $\Gamma = 0$.

| Budget | Cost ($\$10^5$) | Objective Value | Selected Project |
|---|---|---|---|
| Small | 267 | 6047 | 4, 6, 14 |
| Medium | 499.5 | 9123 | 4, 6, 14, 17, 18, 20 |
| Large | 971 | 14687 | 1, 4, 6, 12, 13, 14, 17, 19, 20 |

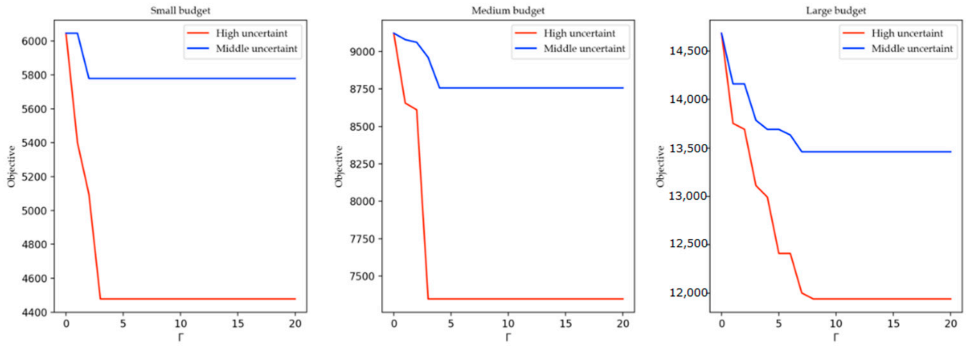


**Figure 2.** Variation of the objective value against Γ changes.

With the results of the ROM, sales, revenue, new purchase price, and revenue were calculated, as shown in Table 6. The parameters for the sales function, $n$, $\alpha$, $\beta_1$, $\beta_2$ and were set as follows. First, the sales period plan $n$ was categorized into three cases: short-, medium-, and long-term. Different sales period plans result in different purchase price strategies, which may impact customers depending on what they are interested in. Hence, different sales and revenue can be anticipated, and 5, 10, and 15 for the cases were set, respectively. $\alpha$ is a ratio factor that controls the investment amount, the sum of the cost of the selected projects, which is reflected in the PC. Since the company may choose not to reflect the overall costs in the PC, the value of $\alpha$ was set as 0.3, 0.5, 0.7, and 1. $\beta_1$ and $\beta_2$ are the impact factors on the sales in the market, and they were set to 0.5:1, 1:1, and 1:0.5, respectively, to check the market response.

With the parameters set, the results of the cases with high uncertainty and large budget are shown in Table 6. As projects are selected by the ROM, the total cost of the selected projects as well as the reduced amount for the *MC* are decided in advance. In the nominal case, the total investment was $97.1 million, and the new *MC* was $102,000 per year. In the worst case, $63.4 million and $105,000 were the total investment and the new MC. In the nominal case, more projects were selected so that the lower new *MC* was calculated, and the larger amount of *MC* was reduced in comparison to the worst case. According to the results shown in Table 6, depending on the planned sales period, the factors for *PC* increase, and the market response, sales, and revenue were quite changed. When the sales planned period was longer, sales and revenue were increased in both the nominal and the worst cases. As the total investment amount was returned for the sales planned period, the purchase price was lowered when the period was longer. As a result, sales in the market were expected to be higher and revenue was larger. Comparing the sales in the nominal and the worst cases, sales in the worst case were higher, as the total investment was lower than that in the nominal case. From the perspective of revenue, when sales were higher, revenue was not always higher as well.

**Table 6.** Results of cases with different parameters.

| Case ($n$, $\alpha$, $\beta_1$, $\beta_2$) | Γ | Sales/Year (Vehicles) | Revenue/Year ($) | PC×(1−$f$($OP$)) ($) |
|---|---|---|---|---|
| 1 | Nominal | 545 | 94,460,440 | 166,650 |
| (10, 0.3, 1, 1) | Worst | 539 | 90,178,130 | 160,840 |
| 2 | Nominal | 533 | 92,579,700 | 167,040 |
| (10, 0.5, 1, 1) | Worst | 531 | 88,959,050 | 161,000 |
| 3 | Nominal | 520 | 90,603,960 | 167,470 |
| (10, 0.7, 1, 1) | Worst | 523 | 87,701,450 | 161,180 |
| 4 | Nominal | 410 | 83,185,360 | 195,060 |
| (5, 1, 1, 1) | Worst | 462 | 84,575,570 | 175,910 |
| 5 | Nominal | 500 | 87,425,790 | 168,200 |
| (10, 1, 1, 1) | Worst | 511 | 85,734,090 | 161,470 |
| 6 | Nominal | 522 | 87,703,810 | 161,430 |
| (15, 1, 1, 1) | Worst | 525 | 85,798,880 | 157,270 |
| 7 | Nominal | 500 | 97,135,790 | 186,880 |
| (5, 1, 1, 0.5) | Worst | 511 | 92,079,090 | 173,420 |
| 8 | Nominal | 533 | 92,579,700 | 167,040 |
| (10, 1, 1, 0.5) | Worst | 531 | 88,959,050 | 161,000 |
| 9 | Nominal | 543 | 90,916,350 | 160,980 |
| (15, 1, 1, 0.5) | Worst | 538 | 87,862,480 | 157,080 |
| 10 | Nominal | 355 | 74,659,240 | 202,090 |
| (5, 1, 0.5, 1) | Worst | 430 | 79,590,550 | 177,880 |
| 11 | Nominal | 464 | 81,792,340 | 169,660 |
| (10, 1, 0.5, 1) | Worst | 483 | 81,413,450 | 162,160 |
| 12 | Nominal | 488 | 82,396,060 | 162,270 |
| (15, 1, 0.5, 1) | Worst | 498 | 81,617,930 | 157,690 |

## 5. Discussion

The concept of sustainability has spread across diverse industries and fields. In particular, in the automobile industry, sustainability has arisen as a critical issue due to the presence of strict regulations. In addition, companies must make an effort to increase their competitiveness in the market by selling their products.

For companies, R&D projects play a major role in determining the sales and revenue of a company, so making appropriate decisions about which R&D projects to pursue is critical. Normally, in an R&D project, a product is updated with new technologies, or a new product is developed. Therefore, project management is important for a company not only to manage projects but also to properly select which projects to pursue.

In the automobile industry, TCO is a critical method for evaluating a vehicle, and a vehicle with a lower TCO can be attractive to customers. A vehicle is developed and updated by R&D projects, so R&D projects can impact a vehicle's TCO. For example, the $MC$ can decrease when new technologies are added or parts are upgraded by a project, and the $PC$ can increase because of the cost of the projects. Therefore, R&D project selection is important for a company because it affects competitiveness and sustainability.

As the projects are an uncertain investment from a company's perspective, a company needs to be prudent when selecting projects. A project has diverse uncertainties in terms of time, cost, and resources, and uncertainty about cost is a top priority concern for a company. To address cost uncertainty in the projects, in this study, the ROM was proposed. The model was tested in the automobile industry environment with different conservatism levels.

As seen in the results, different projects were selected depending on the level of conservatism. When the level was higher, the number of projects selected decreased, and the objective value also decreased. In all cases, when the conservatism level was high, the cost for the value of the vehicle was lower than when the conservatism level was low. However, in terms of revenue, a low conservatism level always had good results when the planned sales period was longer. As shown in cases 5 and 6, the revenue was larger with the low conservatism (nominal case) than the high conservatism level (worst case). With the low conservatism level, the model tends to select a large number of projects, which means a high and aggressive investment, and such a tendency can increase the *PC* for the new product. The *PC* of the product is affected by the planned sales period, and the *PC* is lower when the period is longer. In case 4 (nominal case), as a large number of projects were selected with a short-planned sales periods, the *PC* of the product was high. The expected sales were much lower, and the *PC* was high, which impacted the revenue negatively. As a result, the revenue in the nominal case was lower than the worst case, and in cases 5 and 6, the *PC* of the product was lower than case 4 for both the nominal and worst cases due to a longer than planned sales period. Although the *PC* of the product in the nominal case was still higher than the worst case, the difference in the expected sales volume was small and, thereby, the revenue in the nominal case was higher than the worst case. Therefore, from the perspective of revenue, when making an aggressive investment strategically, a long-planned sales period for the product is recommended.

A company can choose different actions depending on its product strategy. For example, even though revenue may be lost, sales are higher, so a company can expect an additional effect by demonstrating high sales to customers. Alternatively, a company can take a high revenue strategy and invest extra profit from other products. Thus, a company can examine diverse strategies with the ROM.

Another interesting aspect is the variance of sales and revenue in accordance with the investment ratio in cases 1, 2, and 3. In case 1, when 30% of the cost of the selected projects was reflected in the *PC* of the new product, the highest sales and revenue were shown compared to cases 2 and 3. When the reflecting ratio of the investment was larger, the expected sales and revenue were lower. This analysis can assist decision-makers in how the R&D costs reflect the purchase cost of a new product depending on pricing strategy for the new product such as penetration strategy, skimming strategy, and so forth.

This study has several limitations related to ROM. First, the model is cost-dependent, and the projects are cost-oriented. In this model, the cost compared with efficiency becomes the most important factor when selecting projects. Although cost is the most critical factor, there are still other factors that must be considered at the same time. For example, there can be mandatory projects that are required, with high costs. The project duration is not included, as the projects are focused on TCO. The duration can impact the cost of the project and is regarded as another uncertainty.

In future works, the model can be defined in detail by adding other departments of the company. In this case, the resources, scheduling, and duration should be considered. For example, in each department, there are human resources that can manage projects, and the total duration of project completion can be given. If there is precedence between projects, the model can be further developed to allocate human resources to projects in consideration of the precedence of the projects and the uncertainty of the cost and the duration within the total cost and duration limits.

## 6. Conclusions

As global competition intensifies, innovative product companies are concerned with R&D projects for developing technologies to upgrade their products and develop new ones. In addition, as such R&D projects generate profit in the market, project management is critical. However, R&D projects may have uncertainty due to the long duration of the projects. The most concerning uncertainty can be the cost of the projects, since companies operate with limited funds. In this study, to address such cost uncertainty in R&D projects, the ROM is proposed on the basis of the TCO in the automobile industry. In the automobile industry, customers who are interested in purchasing commercial vehicles are very sensitive to TCO because they operate vehicles as part of their business. Such TCO is highly related to the selection of t R&D projects, as vehicles with new technologies are developed by projects that reduce TCO. In addition, when TCO is reduced, customers can use the vehicles for longer and save more money, which is beneficial from both an economic and environmental standpoint. Thus, the TCO is regarded as an important factor for customers and companies.

The proposed model is tested in the automobile industry environment with different conservatism levels in terms of cost uncertainty, and the analysis of the expected market changes and a company's income is performed with the solutions obtained from the proposed model. The result shows that the presented model reacts to cost uncertainty robustly, which assists the decision-makers in the company. In addition, the analysis shows how the changes in solutions caused by the conservatism level variation affect corporate income and the product's sales. It helps decision-makers to evaluate the business strategy in the market and the conservatism level when selecting the projects.

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