International Journal of Production Economics 194 (2017) 52–58

Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Investment performance analysis of industrial products: Case of an effluent processing facility at a chemical company

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ARTICLE INFO

Keywords:
Performance analysis
Industrial products
Customer preference
Subjective factor
Analytic hierarchy process
BOCR analysis

ABSTRACT

This paper proposes an approach to a multi-criteria investment performance analysis of industrial products. Manufacturers must determine the necessary and sufficient specification of products they use. Such an analysis, however, involves a broad range of factors, including some that are subjective. The performance analysis and decision making for investment thus must often rely heavily on past experience, generalities, and intuition. This paper addresses these issues from a benefit, opportunity, cost and risk (BOCR) perspective, in which the criteria are prioritized and the products are evaluated objectively. Pairwise comparisons among the criteria and quantitative assessments of the performance of products comprise a prioritized BOCR analysis. A case study demonstrating the applicability of the proposed approach is conducted at a chemical company. Results show that the proposed approach succeeds in the multi-criteria performance analysis of industrial products, resulting in a practical proposal of a product specification best suited to this company's case.

1. Introduction

Making investment decisions for industrial products costing large sums of money can be quite complicated. Customers must analyze the performance of potential alternatives, and then determine the architecture and specifications of the product, all while being mindful of rapid changes taking place in the technological environment. The difficulties arise primarily from intangible factors, such as customer judgment on criteria that enters into the evaluation and the need to select an appropriate alternative. Confounding the decision-making process is that preferences for products are often subjective. As such, the performance analysis relies heavily on experience, generalities, and intuition, all of which lack transparency and traceability (Tan et al., 2006).

One industry that would benefit from a more objective decision-making process is that dealing with effluent process systems (EPS). Stehna and Bergströmb (2002) proposed a customer-oriented approach to the design of industrial products that could be applied to the performance analysis of an EPS. Their approach, however, did not explicitly incorporate customers' subjective preferences into the design. Because customers were unaware of the factors that were taken into account or how trade-offs were resolved, they were wary of accepting the solution. As a customer of an EPS, a manufacturer faces tremendous challenges in designing the processing system and selecting the appropriate technologies. While many decision-support frameworks have been proposed in the literature (e.g., Tan et al., 2006; De Felice and Petrillo, 2014; Bouzarour-Amokrane et al., 2015), only a few studies have provided systematic models that consider intangible factors such as the customer's judgment of decision criteria.

What is available, though, is objective data, which can provide a quantitative analysis of the specifications of potential alternatives underlying the process in the performance analysis. For example, traditional methodologies for quantitative analysis, such as cost-benefit analysis, are often used to evaluate alternatives. To date, a number of approaches to the performance analysis of industrial products have been proposed. A workable approach to the design of an EPS has been limited, however, as each manufacturer demands its "haute-couture" design of the system, whose details range from the ease of risk management to the green image of the company. Consequently, if we are to include other factors (e.g., opportunities and risks) in the analysis, then performance-analysis approaches that take into consideration only benefits and costs of alternatives do not fulfill the requirements.

To carry out a more robust analysis that optimizes the specification of products for a manufacturer, this paper proposes an approach to a multi-criteria performance analysis of industrial products by combining the

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https://doi.org/10.1016/j.ijpe.2016.12.021
Received 18 April 2016; Received in revised form 29 October 2016; Accepted 12 December 2016
Available online 16 December 2016

Analytic Hierarchy Process (AHP) and a benefit, opportunity, cost and risk analysis (BOCR analysis). The AHP is the measurement method of human perception proposed by Saaty (1980), and has since been disseminated with the development of software (e.g., expertchoice®). Along with the refinement, the AHP has been widely used in a variety of fields because of its user-friendly interface and its compatibility with problems in the real world. The BOCR analysis was developed in the AHP literature as one of evolved cost-benefit analysis (e.g., Saaty, 2001; Saaty and Ozdemir, 2004), which precisely analyzes both pros (benefits and opportunities) and cons (costs and risks) quantitatively. The series of steps of quantification and evaluation in the procedure introduce clarity of thought into the decision-making process.

The multi-criteria performance analysis of industrial products proposed in this paper first requires customers of an EPS to determine the degree of importance of each criterion for the analysis by using the AHP, in which subjective factors in the analysis are quantified. This quantitative information then allows customers to systematically evaluate potential alternatives by conducting a quantitative evaluation followed by the prioritized BOCR analysis proposed in this paper. Note that a refined "rescaled quotient with sum" form is employed as a BOCR function in this paper based on the critique made by Wijnmalen (2007). The results evaluating not only potential alternatives but also criteria for the analysis thus fully justify the final outputs of the analysis. An additional benefit of the revised formulation is that the rationale behind each process of the analysis is captured and can then be used as the basis for a final judgment.

Neither of the methodologies, that is, the AHP or the BOCR analysis, employed here is new. Integrating them, however, provides new insight into industrial problems, thus improving industrial practice and supporting sound decision making. Furthermore, the outcome of this integrated approach suggests the best architecture and specification for a product, which satisfies the industrial requirement and its managerial and economic consequences. Based on traditional analytical methodologies, the performance analysis proposed here provides practical value in industrial applications, as confirmed by the retrospective survey carried out following the case study. Although the proposed approach has been designed for a chemical company, it can be tailored and applied to any manufacturer that desires to analyze the performance of products or investment decisions.

Section 3 describes the research design: outline of effluent processing; the methodology for collecting information on customer preference; and the formulation of the prioritized BOCR analysis. In Section 4, a case study verifying the proposed approach is introduced, in which the architecture and specification of a new EPS is optimized. The implications for a product's supplier in its sales promotion for potential customers are also explored. Section 5 concludes this paper and discusses its limitations and future research directions.

2. Literature review

Much has been written about the technology investment and selection problem, which can be applied to the performance analysis of industrial products (e.g., Sriram and Stump, 2004; Debo et al., 2005; Kasikowski et al., 2008). One of the typical papers on hazardous waste treatment processes, by Evenson and Baetz (1994), adopted optimization methods to solve the selection problem of system design, under the assumption that all information for the system design is quantitatively given for customers in solving the problem. Few models, however, have been developed for the design of an EPS. In EPS design decisions, managers face difficulties selecting the right criteria, as each customer/manufacturer has its unique preference for the system, often expressed as subjective information. In order to cope with such subjective information, many researchers have resorted to the AHP. For example, De Felice and Petrillo (2014) evaluated Italian racecourse performance, and Weifeng et al. (2016) quantitatively analyzed the dangers of water and sand inrush caused by underground mining using the AHP. In addition, Bayazit and Karpak (2007) assessed the readiness of the Turkish manufacturing industry, De Felice and Petrillo (2013) assessed environment, and Tjader et al. (2014) built a cohesive decision model for determining firm level IT outsourcing strategy using the Analytic Network Process (ANP). These approaches explicitly cope with factors considered intangible in evaluations and assessments.

To evaluate trade-offs among BOCR factors, other research employed the AHP or fuzzy AHP, along with a BOCR analysis when evaluating subjects that tend to involve intangibility or uncertainty. Lee (2009a, 2009b), respectively, evaluated the buyer-supplier relationship between manufacturer and supplier, and proposed an analytical approach to the selection of suppliers under a fuzzy environment. Chun-Yueh and Yih-Chearng (2013) presented the model of reverse logistics of the Taiwan photovoltaic industry supply chain, and Tsai and Chang (2013) evaluated the performance of tablet personal computers. Yazdani-Chamzini et al. (2014) and Bouzarour-Amokrane et al. (2015), respectively, proposed a hybrid model to prioritize strategies of investing, and an evaluation and optimization approach for the withdrawal location process in the field of aircraft dismantling. Cho et al. (2015) selected an optimal heating facility for the horticulture and stockbreeding sectors in Korea, and Yap and Nixon (2015) developed multi-criteria decision-making methodology and produced a preference ranking of alternative technologies. The integration of ANP or Fuzzy ANP along with a BOCR analysis were also proposed to evaluate various technologies for new product development (Lee et al., 2011); proper working strategy in a fuzzy environment (Fouladgar et al., 2012); supply chain environmental performance (De Felice et al., 2013); and prototype dependability in software (Mohan et al., 2016).

The above research explicitly took both intangible and BOCR factors into account by integrating multi-criteria decision-making methodologies with a BOCR analysis, which helped promote transparent and traceable decision making. Although a broad range of subjects has been covered, an EPS has not yet been an object of evaluation. Designing a sustainable EPS for manufacturers is essential, as the human and environmental consequences in case of an accident can be catastrophic. In addition, it is not a "one-off" investment necessitating no further investment due to the need to balance the initial costs with the costs of running the system. The system requires a certain amount of margin to be on the safe side, but financial sustainability associated with the life expectancy of the system is also required. The problem, however, is that neither "a certain amount" nor "sustainability" can be uniquely determined because both are a subjective matter for each manufacturer based on its unique preference. Therefore, manufacturers must consider how to resolve "trade-offs" where intangible factors must be dealt with. This paper thus focuses on ascertaining the intangible factors in the performance analysis of industrial products from a BOCR perspective, and proposes a systematic approach to performance analysis combining objective data and subjective preference.

3. Research design

This section outlines effluent processing and details the process of performance analysis of an industrial product. The example used is an EPS in a chemical company that needs massive amounts of capital investment. How to collect information on customer preference for the EPS is then introduced, and a prioritized BOCR is proposed.

3.1. Outline of effluent processing of a manufacturer

An EPS is required in order to purify industrial effluent in accordance with thresholds defined by the law governing effluent processing before being discharged into the environment. The regulations set by the law contain a broad range of items concerning effluent processing, viz. concentrations of Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Suspended Soil (SS). These items relate to the architecture and specifications of processing systems and can be specified as objective data. To purify effluent, an EPS includes several subsystems,

Table 1
Criteria for performance analysis.

Criteria	Definition
D (Benefit)	The cleanliness of discharge measured by the concentration of leaked BOD in effluent (mg/L), whose reciprocal value is identified as Benefit in BOCR analysis.
F (Opportunity)	Flexibility of the installation of an effluent processing system measured by the area of the installation of the system (m^2), whose reciprocal value is identified as Opportunity in BOCR analysis.
C (Cost)	Cost of the system measured by the total amount of initial and running costs (Yen/installation), whose actual value is identified as Cost in BOCR analysis.
L (Risk)	Leakage risk of residuals measured by the total amount of leaked SS (kg/day), whose actual value is identified as Risk in BOCR analysis.

usually a Rotating Biological Contactor (RC), a Fluid Carrier Tank (FT) and a Sedimentation Tank (ST), each of which performs a different function. When all these subsystems are incorporated, an EPS satisfies the regulations. On the other hand, the configuration of these subsystems is not unique, and each different combination has its own advantages and disadvantages. For example, a pure RC system is best at purifying effluent but costs more, while a pure FT design entails lower initial and maintenance costs but has poor process stability. All possible combinations of subsystems must be reviewed for the performance analysis.

Suppliers of an EPS have their own methodologies and techniques for purifying effluent. Thus, once the contamination level of effluent flowing into an EPS is given, requirements for the processing system is specified based on the regulations. According to an interview with the safety supervisors of the chemical company where the case study was carried out for this research, the status of the industrial effluent can be specified by both the volume and the concentration of BOD of inflowing effluent. An EPS then purifies effluent using the three above-mentioned subsystems—RC, FT, and ST. Since the performance of each subsystem is clarified based on its specification, requirements for the system can be satisfied by combining the subsystems in various ways. In addition, both the initial costs and the costs of running each subsystem are also specified. The parameters, that is, a set of criteria for the performance analysis (c) evaluating the system, can be defined as shown in Table 1, where the expected life of the system is 20 years. The four indicators summarized in the table were identified based on discussion with safety supervisors of a manufacturer (customer) and with designers of the EPS (supplier) from a case study; details of the case study itself and of these safety supervisors and designers, will be introduced in Section 4.

Each alternative of EPS must satisfy the requirements defined by the law, such as the cleanliness of discharge or the leakage risk of residuals. Alternatives barely satisfying the regulations would be inexpensive systems but might not be sustainable. On the other hand, alternatives need not err too much on the side of safety, as that would be expensive and might be an over-specification of the system. Customers of EPS must thus resolve this trade-off when selecting a system.

3.2. *Process of performance analysis of a product*

One of the most difficult tasks in the performance analysis of an EPS is how to direct design efforts. Decisions about massive amounts of capital investment are traditionally made by the executive committee of a manufacturer, with the final decision made by consensus. The decision-making process might be inconsistent, however, since subjective factors of the members' preferences for the EPS could affect the outcome of an investment proposal. To rectify the limitations of the existing approach, management would be keen to adopt an approach that could help the executives make decisions that were transparent.

Assuming that the alternatives of the processing system satisfy the regulations, a manufacturer must select one alternative based on its unique preference for the system, such as "cost-saving and robust over the long-term." As the cost and robustness of a system often results in a trade-off, the manufacturer is faced with a dilemma. The manufacturer must therefore accurately analyze the performance of potential alternatives and make decisions on which architecture and specifications of the system to select when the manufacturer's various requirements for the system conflict with each other. Furthermore, the requirements often includes subjective information, such as "flexibility of system at installation," which relates to each aforementioned specification. Quantifying the customer's requirements when analyzing the performance of the system is essential. Thus, the decision-making process must first integrate objective data and subjective requirements (customer preference) for the specification of an EPS, and then evaluate all potential alternatives in light of their advantages and disadvantages. In short, the process thus consists of two main steps: collecting information on the customer preference, and evaluating potential alternatives quantitatively.

3.2.1. *Collection of information on customer preference for EPS*

In the first step of the performance analysis, a customer's preference is represented by four criteria—D (cleanliness), F (flexibility), C (cost), and L (risk) defined in Section 3.1—each of which relates to a specification of the processing system. Information must be collected on a customer's preference in order to convert intangible information into quantitative form. The AHP is ideally suited to quantifying customer preference. The customer must conduct pairwise comparisons of all possible combinations of criteria in order to represent his/her final preference for the specification of an EPS. For example,

> All the following alternatives of EPS satisfy the regulations of effluent processing in your plant but have different features with different architectures. If you compare four criteria c (D, F, C, and L) pair-wise in selecting the best alternative, which criterion do you consider more important for the EPS of your plant, cleanliness of discharge (D) or flexibility of the processing system (F)?

The results of this process quantify the customer's preference for the processing system.

3.2.2. *Quantitative evaluation of potential alternatives*

In the second step of the performance analysis, a quantitative evaluation of potential alternatives in light of advantages and disadvantages can be carried out systematically, since all data representing the status of effluent and the specification of the subsystem (e.g., the concentration of BOD of inflowing effluent into an EPS, and the performance of RC removing BOD) is specified as objective data. Fig. 1 graphically represents the relationship between the collection of information on customer preference and the quantitative evaluation of potential alternatives otherwise known as an AHP model. As shown in the figure, pairwise comparisons reflected a customer's preference are carried out between the goal of the analyses and the decision criteria, prioritizing the degree of importance of each criterion. Then a quantitative analysis based on the objective data of potential alternatives is conducted between the decision criteria and potential alternatives, evaluating advantages and disadvantages of each potential alternative. This integration of the AHP technique and quantitative analysis followed by a multiple-criteria performance analysis comprises the prioritized BOCR analysis.

3.3. *Formulation of prioritized BOCR analysis*

The following parameters, $c_{*,i}$ (c=D, F, C, L), representing the specification of an EPS are employed in the BOCR analysis, where $*$($*$=I: newest, II: contemporary, III: conventional) and i (i=0, …, 8), respectively, denote the architecture of the processing system and the number of RCs of the system, each of which is indexed using the value, where $*$=I and i=0, as a benchmark (set as 1). In this paper, a potential alternative is denoted as ($*$,i). For the merit factors, benefit is defined by the reciprocal value of $D_{*,i}$ (cleanliness of discharge), and opportunity is defined by the

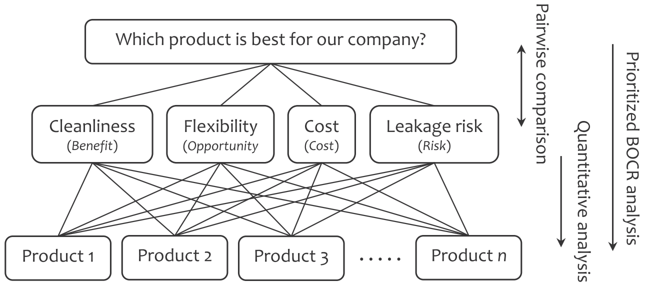

Fig. 1. AHP model.

reciprocal value of $F_{*,i}$ (flexibility of the system installation). $1/D_{*,i}$ represents the cleanliness of discharge, which enhances the "green" image of the manufacturer and would benefit its future corporate activities. $1/F_{*,i}$ indicates the degrees of freedom of the system installation, particularly in laying out the processing system, which increases the opportunity to expand business by using the surplus space of the manufacturer. For the demerit factors, cost is defined by the actual values of $C_{*,i}$ (initial and running costs), and risk is defined by the actual value of $L_{*,i}$ (leakage risk of residuals), both of which can be naturally interpreted as cost and risk in defining a BOCR function.

A BOCR function is then formulated for performance analyses, where p_c (c=D, F, C, L) denotes a customer's preference for criterion c derived from the application of the AHP, explained in subsection 3.2. Since significant differences in variance exist among indicators, each indexed parameter, $c_{*,i}$, is transformed into a T-score of criterion c by the following formula and denoted by $c^{p}{}_{*,i}$,

$$c^{p}_{*,i} \equiv 50 + 10\{c_{*,i} - \mu(c_{*,i})\} p_c / \sigma(c_{*,i}) \tag{1}$$

where $\mu(c_{*,i})$ and $\sigma(c_{*,i})$, respectively, denote the average and the standard deviation of $c_{*,i^*,\ i}$ (c=D, F, C, L). Based on (1), the prioritized BOCR function, $pBOCR_{*,\mathrm{i}}$, can be defined by the following formula, which calculates each alternative's prioritized performance reflecting a customer's preference.

$$pBOCR_{*,i} \equiv \left(1/D^{p}_{*,i} + 1/F^{p}_{*,i}\right) / \left(C^{p}_{*,i} + L^{p}_{*,i}\right) \tag{2}$$

$c^{p}{}_{*,i}$ with p_c=1 corresponds to a normal BOCR function, $nBOCR_{*,i}$, which does not take the customer's preference for criteria into account.

4. Model analyses

This section introduces the procedure and the results of a case study verifying the multi-criteria performance analysis approach proposed in this paper. Company X (Co. X) is a major chemical products company in Japan, whose wide array of products is highly esteemed and ranges from basic materials to fine chemicals. Company Y (Co. Y) is a supplier of an EPS, whose technology in RC is highly rated in the field. Co. Y develops various types of the processing system combining RC and FT, meeting demands from a great many manufacturers. The case study, which was originally a workshop for the optimization of the specification of an EPS in Co. X, was carried out in Japan. The workshop consisted of two executives from Co. X who were in charge of the decision making in the investment, three safety supervisors of three subsystems of the EPS, and two designers of Co. Y who led the design of the EPS in Co. X. During the course of the workshop, technical aspects of effluent processing, including the parameters defining the performance of the system, were discussed, and the above-mentioned experts conducted the evaluation of the system. Although the companies' names, X and Y, cannot be disclosed due to confidentiality agreements, all data presented in this case study are real data from the companies.

4.1. *A case study at a chemical company: performance analysis of EPS*

Upon the renewal of the EPS in Co. X, the management of the company has to decide which alternative of a new EPS to invest in, a decision that would be greatly facilitated by a multi-criteria performance analysis of the products. As noted in the previous section, there are two major factors in effluent processing: (*i*) the total amount of leaked BOD and (*ii*) the concentration of leaked SS. Safety supervisors of Co. X and designers of Co. Y need to design a processing system that satisfies the required level. There are three core subsystems in the EPS—RC, FT, and ST, where ST is designed to be configured at the final phase of the effluent processing. The requirement for the contamination level of effluent into ST is set at the fixed level that Co. X designates. The design of the EPS is thus equivalent to determining the configuration of the remaining subsystems e.g., the number of RC, and the volume of FT.

The performance analysis of EPS is complicated, as it requires selecting the most appropriate combination of subsystems and deciding on the architecture of the EPS from among a great many potential alternatives. Based on the prioritized BOCR analysis approach proposed in this paper, the safety supervisors of Co. X and the designers of Co. Y identify a set of criteria for the new EPS, which are listed as parameters in subsection 3.3. Three safety supervisors of Co. X are interviewed in order to identify criteria, each one in charge of the safety of one of the three subsystems (i.e., RC, FT and ST). Two designers of Co. Y committed to determining the criteria are the chief and sub-chief of the EPS design. Criterion c assesses the potential benefits of the new system (benefit: $1/D$); its alignment with the company's strategy (opportunity: $1/F$); its costs for identified objectives (cost: C); and its failure risks (risk: L). In this approach, potential alternatives of the processing system are evaluated by the set of criteria, c. The alternative with the highest BOCR scores is then approved as the new EPS.

Co. Y first proposes some alternatives of the EPS, each of which satisfies the required level of Co. X. Leaving out the actual raw data regarding the specifications of EPS here, the indexed details of the alternatives, that is, the specifications of the potential processing systems, are summarized in the Appendix A. Co. X then represents its preference for the processing system; Table 2 summarizes Co. X's preference for the system quantified by the AHP. In determining p_c, the two executives of Co. X who were in charge of the decision making in the investment conducted pairwise comparisons. In the process, they considered all aspects of the EPS and individually determined the relative importance of each c among four criteria. Their geometric mean was then assigned to a pairwise comparison matrix, which reflected the degree of importance of the four criteria. As can be seen in Table 2, Co. X emphasizes the degree of importance of the initial cost, $C_{*,i}$, as the highest, and cleanliness of discharge, $1/D_{*,i}$, as the second highest, and so on. The set of the degrees of importance can be interpreted as Co. X's preference for the EPS, which needs be reflected in the design of the new processing system.

Table 3 summarizes the results of the BOCR scores, and Fig. 2 illustrates the rankings of the alternatives shown in the table. A normal BOCR score of a potential alternative (*,i), $nBOCR_{*,i}$ calculated by (2) with p_c=1, is shown by a solid line. A prioritized BOCR score of a potential alternative (*,i), $pBOCR_{*,i}$ calculated by (2), is shown by a dashed line, in which Co. X's preference shown in Table 2 is represented as p_c. As summarized in the Appendix A, the score of *O* (Flexibility) drastically changes in its value in comparison with the other criteria *B* (Cleanliness), *C* (Costs) and *R* (Leakage risk). This difference results in higher scores of alternatives with a greater

Table 2
Company X's preference for the EPS.

Parameter	$1/D_{*,i}$(Cleanliness)	$1/F_{*,i}$(Flexibility)	$C_{*,i}$(Costs)	$L_{*,i}$(Leakage risk)
p_c	0.352	0.149	0.365	0.134

Table 3
Results of BOCR analyses.

System architecture	$nBOCR_{*,i}$	$pBOCR_{*,i}$
I,0	1.0288	1.0057
I,1	1.0104	1.0019
I,2	1.0208	1.0055
I,3	1.014	1.0037
I,4	1.0021	1.0001
I,5	1.0038	1.0008
I,6	1.0029	1.0004
I,7	0.9951	0.9979
I,8	0.9932	0.997
II,0	1.0077	1.0008
II,1	0.9903	0.9971
II,2	0.9961	0.9991
II,3	0.9979	1.0002
II,4	0.9897	0.9979
II,5	0.9911	0.9984
II,6	0.9926	0.9988
III,0	0.9913	0.9973
III,1	0.9922	0.9988
III,2	0.9884	0.9983
III,3	0.9927	1.0002

number of RC, that is, with less volume of FT. As shown in Table 3, the normal BOCR scores of $nBOCR_{I,0}$, $nBOCR_{I,2}$ and $nBOCR_{I,3}$ are the top three, while the rank order of these alternatives based on $pBOCR_{*,i}$ is exactly the same as that of $nBOCR_{*,i}$. Therefore, the primary results of the prioritized BOCR analysis are almost identical to those of a normal BOCR analysis, which means that the judgment of the executives of Co. X falls in almost the same direction as the normal BOCR analysis implies.

4.2. *Implications for the sales promotion of a supplier for potential customers*

By using the prioritized BOCR analysis, sensitivity analyses of customers' preferences can be conducted, and how preferences for a product would affect the results of the selection would be clarified. The results from the analyses hint at how Co. Y might promote its product to potential customers. Leaving aside the details of prioritized BOCR scores, Fig. 3 shows the results from the sensitivity analyses of different preferences, summarizing the rankings of the potential alternatives, as shown in Fig. 2. Fig. 3 shows the rankings of alternatives based on prioritized preferences, such as opportunity (flexibility of the system installation) prioritized, cost (initial and running costs) prioritized. In the analyses, each preference is artificially generated by perturbing the values of pairwise comparisons so as to emphasize the degree of importance of a criterion. For example, opportunity prioritized preference, *O* prioritized, is generated by setting the relative importance of opportunity as "9" (absolutely important) to all the remaining criteria in pairwise comparisons, and fixing the relative importance among the remaining criteria as "1" (equivalent) in all remaining pairwise comparisons.

As with the analyses in the previous section, significant differences in scores of *O* (Flexibility) in comparison with the other criteria result in a drastic change in the ranking of alternatives. For instance, a potential alternative (I,8) designed on the newest architecture with more RC is ranked at the top based on *B* prioritized preference; based on *C* prioritized preference, however, the alternative is ranked as the worst, where the normal BOCR analysis ranks it 12th among 20 alternatives. This result is considered to be induced by the number of RC that can effectively purify effluent but at great cost. As a result, the rankings of alternatives change drastically according to the preferences, suggesting a different selection of effluent processing system for the customer. Furthermore, the sensitivity analysis clarifies the pros and cons of each alternative based on a customer's preference, thus suggesting to the supplier how to promote its products.

Retrospective interviews were carried out following the workshop with the safety supervisors of Co. X and the designers of Co. Y. Based on the interviews, the proposed multi-criteria performance analysis succeeded in enhancing managerial decision making by improving transparency and traceability. In the analysis, trade-offs among various criteria could be quantified using the AHP (Table 2) and the decision could be made with high transparency (Fig. 2). Moreover, the approach provided a flexible decision-making framework that could take different focuses on evaluation into consideration when another preference for the processing system would be expressed. The prioritized BOCR analysis thus enabled the safety supervisors of Co. X to gain better insight into the evaluation and selection of a new processing system in a complicated situation (customer's perspective).

Co. Y's designers were also satisfied with the prioritized BOCR analysis that could address different customers' preferences (Fig. 3). The approach proposed in this paper clarified the pros and cons of each potential alternative based on a customer's preference, which could, in turn, help designers of Co. Y address various customers' requirements (preferences) and optimize the design of an EPS with its own technologies in their sales promotion for potential customers (supplier's perspective).

In contrast to the approach proposed in this paper, existing approaches to performance analysis could never sufficiently address the EPS selection problem while taking subjective factors into account. Neither questions such as why the component and architecture of the

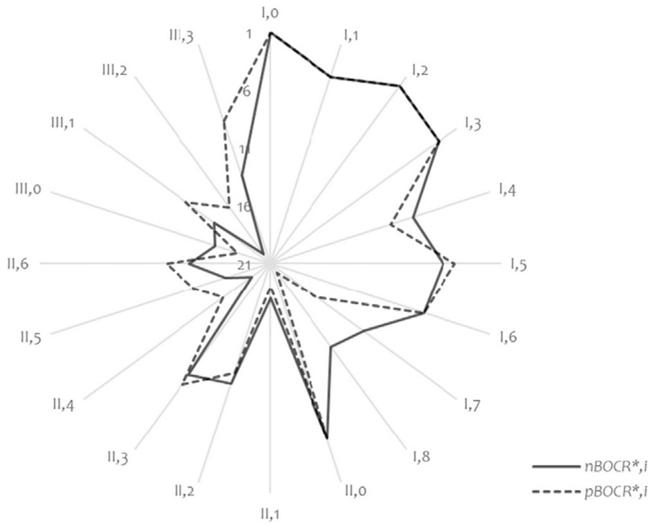

Fig. 2. Results of BOCR analyses (rankings of alternatives).

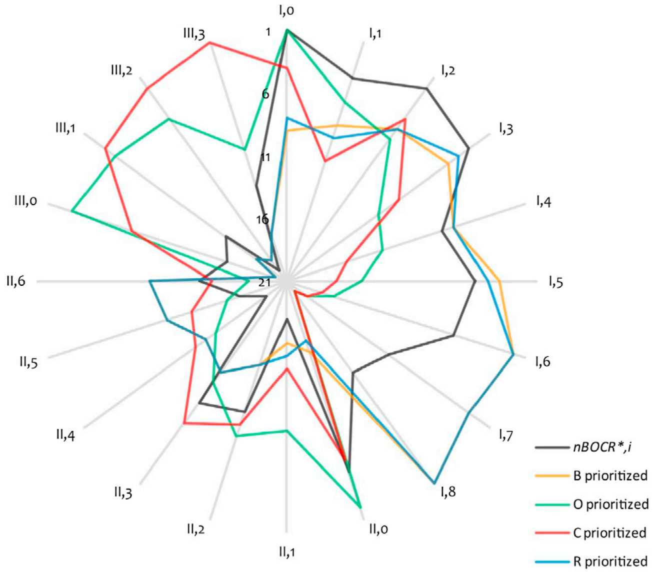

Fig. 3. Results of sensitivity analyses (rankings of alternatives).

processing system was selected nor what the benefit of the selected system was could be easily answered. The multi-criteria performance analysis combining the AHP and the BOCR analysis proposed in this paper provides a framework for considering the impact of each trade-off decision on the criteria, and develops a clear decision path for a manufacturer that justifies massive investment in an EPS.

5. Concluding remarks and future research

This paper proposes an approach to multi-criteria performance analysis of industrial products and subsequently optimizes the specification of a product for a manufacturer in which an EPS is employed as one of the industrial products requiring massive amounts of capital investment. The performance analysis integrates objective data and subjective preference for products, and not only satisfies the legal requirement, but also takes customer preference into account in the design of the product. The approach contributes to making the decision path more transparent and solid than traditional approach could do. The case study demonstrates the applicability of the approach that supports customers in designing an EPS, in which the best architecture and specifications for the product were identified. The application of the AHP is a simple approach to transforming subjective information into objective data, while the BOCR analysis is a systematic approach to evaluating the performance of the system. The proposed approach, therefore, allows a manufacturer to deal with these objective data and subjective information on the same horizon. By providing clarity to the process of the performance analysis, the decision-making results are transparent and traceable.

Since an EPS requires massive amounts of capital investment, many company executives will face this decision-making process. Such as the case of group decision making, diverse ideas and opinions affect the decision-making process, which sometimes results in confusion among decision makers. While a number of approaches to the performance analysis of industrial products have been proposed, approaches to the design of an EPS have been limited. In addition, even though many decision-support frameworks have been proposed, little research has provided a systematic model that considers intangible factors. The multi-criteria performance analysis proposed in this paper is thus significant, as each decision criterion and evaluation result can be clarified at each decision-making step. The approach can be applied to more general supply chain management, such as for build-to-order products ranging from personal computers to custom-built homes. The approach also provides potential customers of such industrial products with a good opportunity to reflect on their preferences for the product. This process supports their decision making and makes them feel justified in making the purchase. Moreover, the proposed approach allows managers to have a clear decision path that provides traceability, enabling managers to revisit how the decision on an EPS was reached. Even though the proposed approach has been applied to the case of an EPS, it can be tailored and applied to any manufacturer or service company analyzing the performance of products or making investment decisions.

This paper demonstrates that a new integrated approach to multi-criteria performance analysis is effective. The companies in the case study acknowledged that the approach gave them an overview of the issues affecting EPS performance and provided them with a structured way of seeking to improve. Particularly, the prioritized BOCR and sensitivity analyses allowed them to communicate and make decisions effectively. In short, the BOCR model helps to address the shortcomings of existing approaches (e.g., Weifeng et al., 2016; Tjader et al., 2014; Tsai and Chang, 2013) by giving a clear and systematic approach to analyzing and diagnosing a particular problem. In addition, the proposed approach allows managers to consider various factors that are key to making sound EPS decisions. Specifically, both the positives (benefits and opportunities) and negatives (costs and risks) are quantitatively analyzed, and intangible factors are dealt with in the decision-making process.

Nonetheless, the proposed model has some limitations. Further research needs to explore the following issues: the pros and cons of indexing indicators, and the selection and definition of parameters. In this paper, all indicators are indexed by a benchmarking alternative, since each indicator has a different unit. In addition, those indexed indicators are transformed into a T-score due to their significant differences in variance. This indexing and transformation of indicators for the prioritized BOCR analysis should be explored further. As for the selection and definition of parameters that relate to the specifications of industrial products, experts in the design of products discussed and determined parameters, which was plausible for the case study. On the other hand, how to define parameters identifying specifications of the system, such as the reciprocal value of $D_{*,i}$ for the benefits of cleanliness of discharge, is an open-ended question. Indeed, identifying a decision maker's utility function of indicators representing the performance of a product is quite challenging. The approximation of the utility in the formulation of analyses may be inevitable, and should be explored in future research.

Appendix A. Specifications of potential alternatives of EPS proposed by Company Y

System architecture	Number of RC	Volume of FT	*B*(Cleanliness)	*O*(Flexibility)	*C*(Costs)	*R*(Leakage risk)
I (Newest)	0	791	**1.00000**	**1.00000**	**1.00000**	**1.00000**
	1	791	1.04163	0.64602	1.08541	0.96003
	2	528	1.09188	0.60036	0.99951	0.91585
	3	528	1.14298	0.47837	1.07353	0.87490
	4	396	1.11957	0.42740	1.16206	0.89320
	5	396	1.17484	0.36173	1.16762	0.85118
	6	317	1.23012	0.32242	1.21763	0.81293
	7	264	1.22934	0.28716	1.29140	0.81345
	8	264	1.28730	0.25594	1.35788	0.77682
II (Contemporary)	0	791	0.81613	1.00000	0.99688	1.22530
	1	791	0.84944	0.64602	1.07318	1.17725
	2	396	0.84374	0.67104	1.00732	1.18520
	3	317	0.89027	0.54727	0.98887	1.12325
	4	264	0.90237	0.45287	1.05562	1.10819
	5	226	0.95167	0.38624	1.07010	1.05078
	6	226	0.99800	0.33181	1.08269	1.00200
III(Conventional)	0	791	0.69364	1.00000	0.98750	1.44167
	1	528	0.72016	0.80585	0.92477	1.38859
	2	264	0.71048	0.73602	0.91752	1.40751
	3	226	0.76628	0.57486	0.87811	0.00500

Each criterion is indexed by the specification of an alternative, (I,0) as a benchmark (shown in bold).

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