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AN OPTIMAL DESIGN METHOD FOR PRODUCT-SERVICE SYSTEMS USING AN INVENTIVE DESIGN APPROACH

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ABSTRACT
In the context of rising market competition, diverse customer needs, and increasing environmental concerns, product-service systems (PSS) are gaining attention for achieving financial benefits and resource efficiency. Existing research on PSS design has applied multi-objective optimization methods to derive solutions that meet the requirements of multiple stakeholders. However, when strict constraints exist among PSS design requirements and their realization, simple optimization often fails to satisfy all stakeholders. To address this, the paper focuses on the inventive design approach, which facilitates creative solutions for problems that are difficult to solve through optimization. This study proposes a method to support the optimal design of PSS by integrating TRIZ, an inventive design approach. The proposed method is demonstrated in a PSS design case for automated valet parking. Application results demonstrate that the method enables designers to resolve physical contradictions through a comprehensive, top-down design approach.

Keywords: Product-service systems, Design optimization, Multi-objective optimization, Inventive design, TRIZ

1 INTRODUCTION

Amid intensifying market competition, diverse customer needs, and growing environmental concerns, product-service systems (PSS) [1] are gaining attention as a means of achieving financial benefit and resource efficiency. PSS addresses these issues by integrating products and services and involves collaboration among stakeholders with different requirements [2]. Enhancing stakeholder satisfaction is crucial while considering trade-offs from the conceptual design stage to define the PSS concept and construct a solution that optimizes various stakeholders' requirements. However, the diverse requirements and resulting trade-offs make it challenging to derive a PSS design that satisfies all requirements simultaneously.

In engineering design, multi-objective optimization is considered an effective approach for optimizing multiple objective functions, which quantify requirements, under constrained conditions during the conceptual design phase [3]. However, in PSS design involving multiple stakeholders, value ranges may not simultaneously satisfy all requirements, and the objective functions and parameter conditions required for components (functions and attributes) may be unknown. Therefore, optimization that merely searches under constraints is not viable. Design solutions must be derived by compromising initial requirements, expanding the search space, and relaxing constraints. These solutions do not fully satisfy each requirement and deviate from the original optimization goal. To address this issue, this study focuses on the inventive design approach, which enables creative solutions for problems difficult to solve through optimization. Specifically, we propose a method to support PSS design by integrating TRIZ [4], an inventive design approach for solution generation.

2 RELATED STUDIES

2.1 Routine and inventive design in solution search

There are two types of problems in design solution search: those solvable by optimization and those challenging to solve with optimization [5]. The former, known as "routine design," involves a minimum of one solution within the search space, enabling an efficient search using established optimization methods. The latter, termed "inventive design," is difficult to address with existing methods and requires a novel, creative approach involving trial and error to find a solution. While routine design efficiently optimizes, it often results in a compromise when no suitable framework exists. By contrast, inventive design, unconstrained by existing frameworks, may avoid compromise by generating innovative solutions. The comparison between two design approaches is presented in Table 1.

Table 1. Comparison between routine design and inventive design [6]

Routine design	Inventive design
Manage what is known	Discover what is unknown
Optimization of existing data for best result	Moving further ahead from the optimized result of existing data
Incremental improvement	Radical innovation
Accept compromise as a potential solution	Refuse compromise as a potential solution

2.2 TRIZ and PSS design

TRIZ is an innovative problem-solving methodology, developed by Altshuller and Altov (1996) through the statistical analysis of a vast amount of patent literature in various technical fields [4]. It represents a representative approach to the original design. In TRIZ, contradictions are classified into three levels according to the level of abstraction. In TRIZ, several tools have been proposed to detect contradictions in the design and to eliminate or mitigate the relationship between the contradictions according to the levels of contradiction. Contradictions are classified according to their level of abstraction into the following three levels.

- Administrative Contradictions: The situations where improvement is required, but the solution remains unknown.
- Technical contradictions: The classical engineering trade-offs, where you cannot reach the desired state because something else in the system prevents it.
- Physical contradictions: The situations in which an object or system suffers contradictory, opposite requirements.

The 40 Inventive Principles provide a framework for addressing contradiction problems, offering a set of ideas based on the 40 inventive principles for technical contradictions and the principle of separation for physical contradictions. The former comprises a set of 40 general-purpose abstract solution ideas, including such concepts as "division" and "asymmetry," which are employed to obtain conceptual solutions for technical and physical contradictions. The contradiction matrix, a tool provided by TRIZ, can be employed to identify inventive principles that resolve contradictions. The principle of separation is a technique for deriving solutions to physical contradictions, which consists of four fundamental separations: (1) separation in space, (2) separation in time, (3) separation between part and whole, and (4) separation between conditions.

In the field of PSS design, a range of TRIZ-based design support methodologies have been investigated [7]. Initially, researchers verified the effectiveness of TRIZ adoption for a new and inventive PSS concept-generation [8,9]. Several studies suggested an approach to generating a new PSS concept by providing 40 inventive principles of TRIZ for PSS [10,11]. Furthermore, the innovative design support for PSS has been addressed by combining TRIZ with several methods such as quality-function deployment (QFD) [10] and case-based reasoning [12]. The intricate nature of PSS structures and their interdependencies frequently gives rise to trade-offs, necessitating the application of inventive design approaches such as TRIZ in PSS designs. However, identifying the optimal solution in such PSS designs solely through inventive approaches, which often entail trial and error, is a challenging endeavor. TRIZ is a qualitative method, and it is not feasible to confirm whether a solution was truly generated within the search space through its application to PSS design.

2.3 Optimal design support for PSS

Some studies have proposed PSS design methods using optimal design approaches. Song et al. (2015) examined the trade-offs among stakeholders in designing elevator services, focusing on optimizing service performance, minimizing service costs, and reducing response time [13]. Similarly, Bal et al.

(2020) developed a model to determine the optimal placement of recycling facilities. Their approach balanced "efficiency of product collection from customers" and "transportation costs" with social benefits such as improved access to medical facilities and public safety for employees at each facility [14]. Although these studies proposed multi-objective optimization methods for specific PSS cases, these models are only applicable to individual scenarios. Applying them to various PSS designs with differing requirements is difficult. Specifically, the design variables required to express the objective function, the determination of constraints, and the formulation process using these variables have not been formalized. Additionally, no general guidelines exist for PSS designers to optimize their solutions. To address this, Tsuji et al. (2022) proposed a general-purpose multi-objective optimization method for PSS design. This method formulates the objective function by setting and evaluating parameters based on stakeholder requirements [15].

2.4 Approach of this study

Due to the complexity of PSS requirements, driven by diverse stakeholders, an inventive design approach is essential. However, finding an optimal solution in PSS design using this approach (i.e., TRIZ) alone is challenging and involves trial and error. This paper proposes a methodology to support PSS design optimization by applying TRIZ to specific elements of the PSS structure, identifying factors that hinder optimization. The study focuses on the "physical contradictions among requirements and functions related to the same attribute," a key factor in trade-offs. Using TRIZ's "Separation principle," physical contradictions are separated from constraint conditions, as shown in Figure 1 (I). This approach resolves trade-offs by eliminating the overlap between constraints and requirements, enabling PSS design optimization. The key principles of the proposed method are outlined below.

Identification of physical contradictions

First, the physical contradictions within the PSS structure must be identified. Given the complexity of PSS requirements, the initial step involves identifying the components to be designed and their interdependencies. Next, the components that cause physical contradictions—trade-off factors—are identified.

Resolving physical contradictions through separation

Once the attributes causing the physical contradictions have been identified, the overlap between the constraints of the requirements is examined. This involves determining whether a value range exists that can simultaneously satisfy all requirements. When the constraints do not overlap and standard optimization is not applicable (Figure 1 (I)), the separation principle is employed to resolve the physical contradiction. For instance, as illustrated in Figure 1 (II), the value ranges of the attribute related to requirement A (α) and the attribute related to requirement B (β) are established independently to differentiate the constraint conditions. When individualizing constraint conditions for a specific attribute, appropriate value ranges must be set for related attributes that depend on it. Based on the identified dependencies in (I), clustering is performed to determine which attributes should be considered together when applying separation. This outcome is then incorporated into the entire PSS structure, allowing for the individualization of constraint conditions for specific attributes.

Confirmation of design solution appearance

As previously mentioned, the inventive design approach is employed when solutions are not readily apparent through routine design methods. Specifically, a solution may not exist within the search space following the separation process. Therefore, the suitability of the separation is assessed by determining whether a solution is present within the search space through a solution search conducted under the individualized constraints resulting from the separation. During this process, it is essential to formulate each requirement into an objective function and incorporate the outcomes of the separation into this formulation. This study employs a proposed formulation support method for PSS optimization design [15] to convert each requirement into an objective function. This approach enables the reflection of the separation results in the design problem formulation, as detailed below.

- In the case of a design variable x representing a separated attribute, the upper and lower bounds of each constraint condition are set as threshold values (x_α, x_β), as illustrated in Figure 1 (II).
- While maintaining the objective function targets (f_1, f_2) at the threshold, they are formulated separately as ($f_{1\alpha}$, $f_{2\alpha}$) and ($f_{1\beta}$, $f_{2\beta}$) according to the circumstances under each constraint

condition.

- Optimization is performed for each combination.

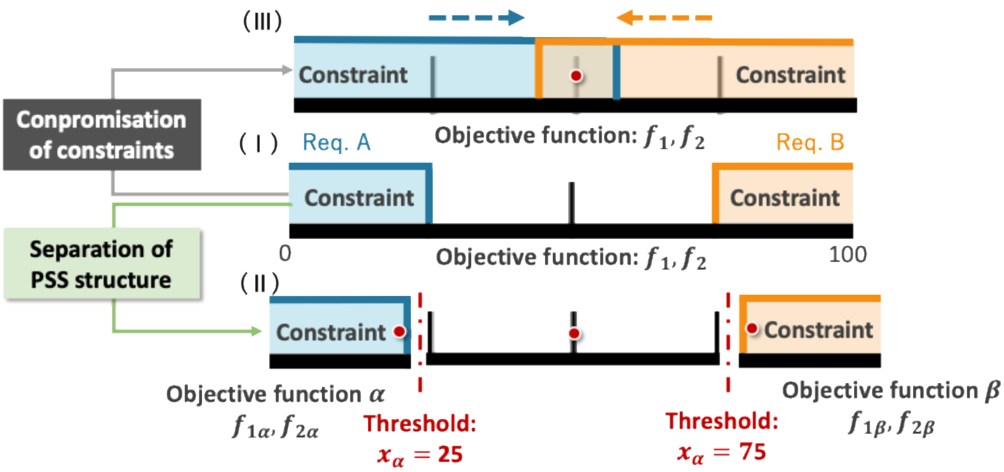


Figure 1. Separation approach of this study

3 PROPOSAL

The proposed method comprises five steps based on the approach described in Section 2.3. The following subsections detail each step, and the overall procedure is illustrated in Figure 2.

3.1 Step 1: Identification of components of PSS

To identify the components of the PSS, a functional deployment based on the view model [16] is first conducted to clarify the functions and attributes that fulfill the requirements of each stakeholder. The view model serves as a tool that represents the quality elements provided to customers as requirements and expresses the structure of the PSS in terms of requirements, functions, and entities. By constructing a view model for multiple requirements, the components of the PSS are clarified.

3.2 Step 2: Identification of dependencies and physical contradictions between components

To investigate dependencies among the components identified in Step 1, a multiple domain matrix (MDM) [17] is constructed by integrating the design structure matrix (DSM), which describes dependencies between elements in the same domain, and the domain mapping matrix (DMM), which describes dependencies between elements in different domains. To assess the impact of changes in a specific element on others, the relationships between elements in the same domain—such as requirements, functions, and attributes in the DSM—and between elements in different domains, such as requirements and functions or functions and attributes in the DMM, are evaluated based on the criteria shown in Table 2. When functions marked as "-2: inhibit" in the function DSM are analyzed in the function-attribute DMM as being caused by competing values of the same attribute, they are identified as physical contradictions.

Table 2. Evaluation criteria of MDM

Matrix		Evaluation criteria
DSM	Requirement	0 : No influence, -1 : Trade-off
	Function	2: Necessary, 1: Preferable, 0 : No influence, -1: Not- Preferable, -2: inhibition
	Attribute	1 : Influential, 0 : No influence
DMM	Requirement-Function	1 : Influential, 0 : No influence
	Function-Attribute	1 : Influential, 0 : No influence

3.3 Step 3: Clustering of PSS components

To comprehend the elements considered during separation in TRIZ, it is necessary to cluster elements with positive dependencies (2: necessary/1: preferable) in the function DSM and dependencies (1: influential) in the attribute DSM, based on the matrices constructed in Step 2. This creates functional and attribute clusters that are essential for realizing PSS.

3.4 Step 4: Separation of PSS structure

If the physical contradiction identified in Step 2 is deemed inapplicable by conventional optimization procedures after assessing constraint conditions, the contradiction is resolved through separation. Specifically, based on the TRIZ separation principle, attributes are separated to ensure the satisfaction of each function and requirement. The value range of attribute A1 for requirement R1(α) and the value range of attribute A1 for requirement R2 (β) are established as discrete entities to differentiate the constraints (Figure 3). Accordingly, when individualizing the constraint conditions for attribute A1, appropriate value ranges must be set for surrounding attributes that are dependent on or function in contradiction with it. The outcomes of the separation are then reflected in other attributes, A2 and A3, which belong to the same cluster AC1, as identified in Steps 2 and 3. This allows the specific constraints associated with attribute A1 to be integrated across the entire PSS structure, facilitating the formulation of the objective function under individualized constraints based on the effects of separating specific attributes across multiple attributes.

3.5 Step 5: Multi-objective optimization of PSS design

Step 5-1：Setting objective parameters

In cases where a requirement directly conflicts with another, a quantitative and objective parameter is established as the objective parameter (OP) to be optimized. For instance, if the requirement is to "reduce environmental load," it is preferable to define parameters such as "CO_2 emissions" or "water consumption" rather than vague terms such as "size of environmental load," which are challenging to quantify. It is essential to ascertain whether the optimization of the OP is being achieved, specifically whether the OP is being minimized or maximized.

Step 5-2：Setting design variables and constant parameters

In this step, the attributes from the view model created in Step 1 are considered potential design variables. The designer subsequently classifies the variables based on two criteria: first, whether their values can be manipulated for each attribute; and second, whether their effects on the satisfaction of each OP should be considered. Even for attributes that can be manipulated, if they do not impact the fulfillment of the OP, they can be excluded from the formulation.

Step 5-3：Formulation of requirements

As illustrated in Step 4, each OP is expressed using design variables and constant parameters to formulate an objective function. As demonstrated in Section 2.3, the upper and lower limits of each constraint condition are defined as threshold values (x_α, x_β) for the design variable x, representing the separated attributes. The objective function (f_1, f_2) is maintained at these values but is formulated independently according to the constraint conditions as ($f_{1\alpha}$, $f_{2\alpha}$) and ($f_{1\beta}$, $f_{1\beta}$).

Step 5-4：Implementation of optimization

Finally, optimization is performed for each combination, and the occurrence of solutions in both search spaces is mathematically evaluated to ascertain the efficacy of the separation. If the solution obtained fails to satisfy the requirements, it may be difficult to determine the underlying cause based solely on the output results. In such cases, designers should return to each step and systematically examine the attributes to be separated, the separation methods employed, and the formulation itself to derive a solution that satisfies both requirements.

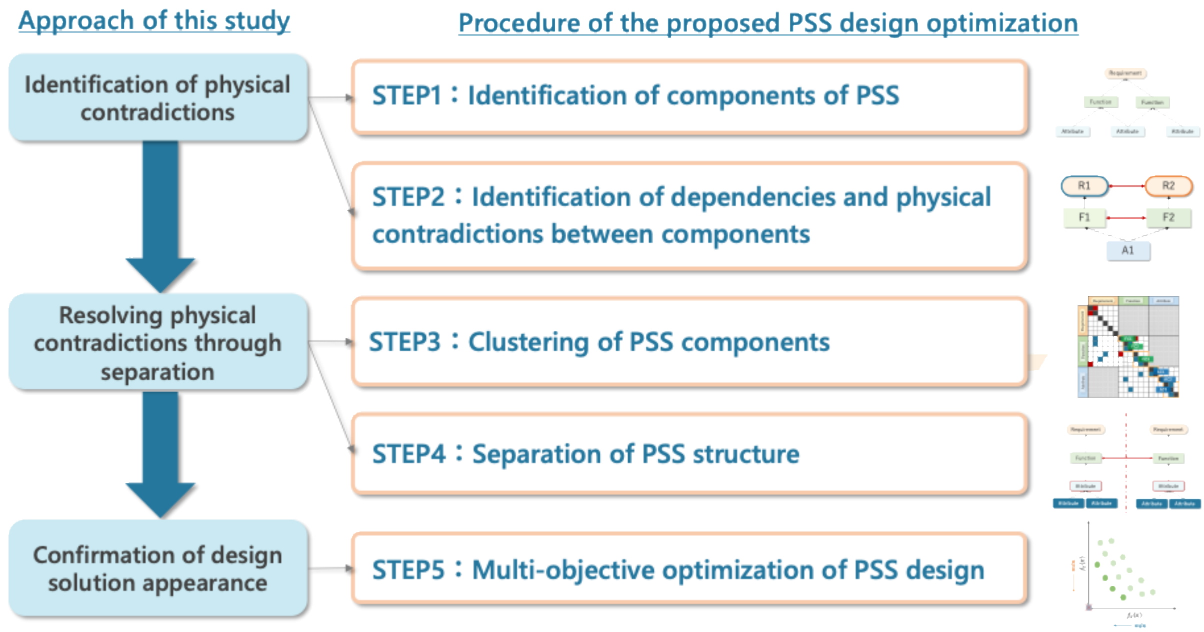


Figure 2. Overview of the proposed method

4 CASE STUDY

4.1 Description of the target case

To verify the usefulness of the proposed method, it was applied to a case involving the introduction of automated valet parking (AVP) at Lyon Airport in France [18]. This service utilizes automated driving technology to park vehicles automatically in a parking lot. Once the driver has entered and exited the designated area, the automatic guided vehicle (AGV) performs a series of operations on their behalf, including entry, transportation, and exit. In this case study, the various stakeholders involved in this PSS were identified, including airport customers, system integrators, parking lot operators, and other relevant parties. Their requirements were extracted and are shown in Table 3.

Table 3. Stakeholders and their requirements

Stakeholder	Role	Requirements
Airport user	Visit the airport for boarding and shopping	R1: Reduce parking fee
		R2: Reduce waiting time
		R3: Ease of retrieving luggage
Equipment provider	Provision of AGV equipment that is part of an AVP system	R4: Increase customer satisfaction
System integrator	Introduction and operation of AVP system	R2: Reduce customer waiting times
Parking operator	Lease land from airport to operate parking lot	R5: Improve operational efficiency
		R6: Ensure safety in the parking lot

4.2 Step 1: Identification of components of PSS

The components of the PSS involved in realizing each stakeholder's requirement were identified using the view model. For instance, the view model for the customer's requirement "R1: Reduce parking fee" identified "discount based on conditions" as a function to meet this requirement and "parking location from the boarding/exiting area" as an attribute related to this function.

4.3 Step 2: Identification of dependencies and physical contradictions between components

Figure 3 shows the result of constructing the MDM based on the components identified in Step 1. For instance, "F1: discount if parking position is far away" and "F12: move parking position closer to the boarding/exiting area" were identified as exhibiting a value of inhibition (-2) toward each other. This is due to their classification as physical contradictions stemming from the same attribute, "A1: Parking position from boarding/exiting area," in the function-attribute DMM. Furthermore, the requirement-function DMM corroborates that the inconsistency between the two functions represents a trade-off between the requirements "R1: Reduce parking fee" and "R2: Reduce waiting time."

4.4 Step 3: Clustering of PSS components

Figure 3 shows the outcomes of the clustering process conducted in MATLAB, based on the dependencies identified in Step 2. For instance, the attribute clusters "AC1: Exit time" and "AC3: Parking fee" were identified as being associated with the function "F1: Reduction in the parking fee if the parking position is situated at a distance."

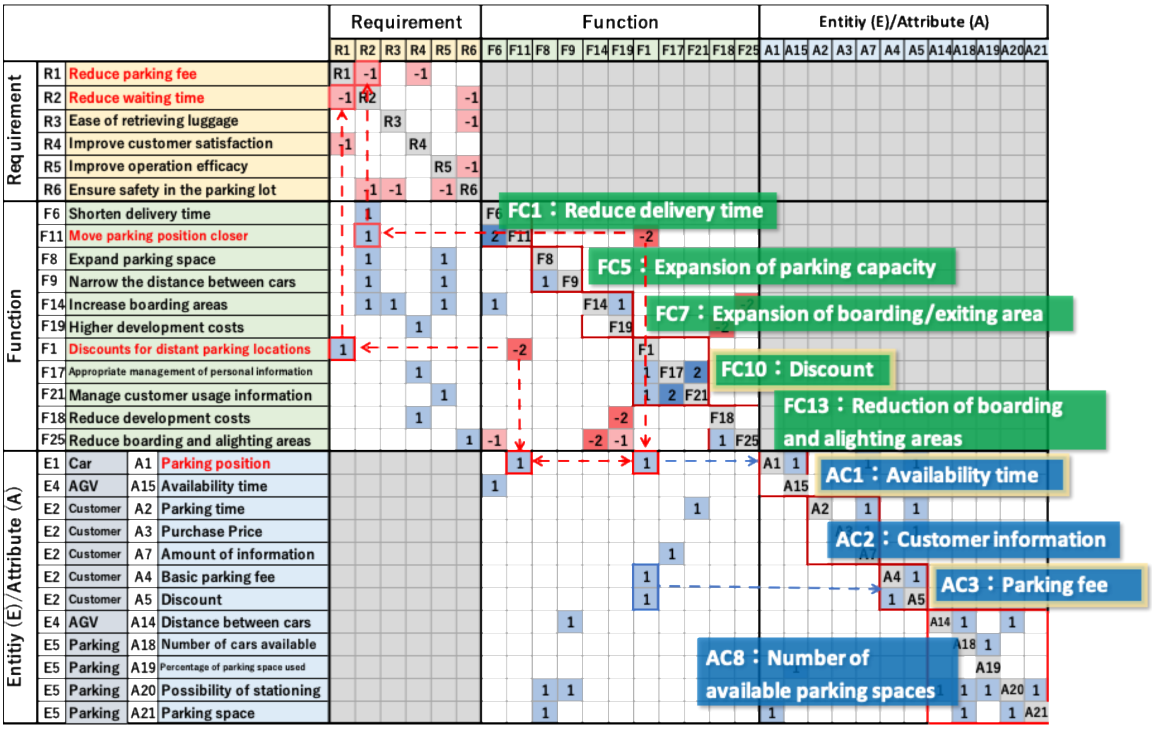


Figure 3. Part of the structured MDM

4.5 Step 4: Separation of PSS structure

A review of the constraint conditions for the same attribute, "A1: Parking position from boarding/exiting area," revealed a physical contradiction between the functions "F1: analysis of the discount if parking position is far away" and "F11: parking position closer to boarding/exiting area" (Table 4). No overlapping range was found between the constraint conditions, resulting in no solution that can satisfy both requirements simultaneously. Thus, the factor impeding the realization of both functions is the physical contradiction of the spatial attribute of the parking location. To address this, we separated this contradiction from a spatial perspective. This separation was also reflected in the attributes "A6: Exit time" and "A4: Discount rate," which should be considered concurrently.

Table 4. Result of separation

		Perspective of separation: space	Elements should be considered concurrently		
Target of separation		A1: Parking position from boarding/exiting area (AC1)	A6: Availability time (AC1)	A5: Basic parking fee (AC3)	A4: Discount fee (AC3)
Separation result	α	Close	Short	Fixation	No discount
	β	Far	Long	Fixation	Discount

4.6 Step 5: Multi-objective optimization of PSS design

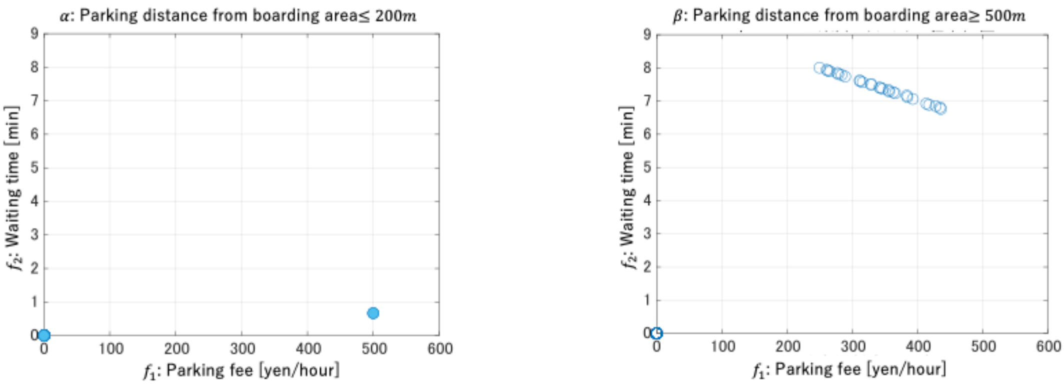
Based on the separation results, the upper limit of the constraint condition for requirement R2 was set for α, while the lower limit of the constraint condition for requirement R1 was set for β as threshold values. In light of the data presented in Table 5, the objective function was formulated in a simplified manner as Equations (1) and (2).

Table 5. Formulation of the PSS design

Parameter	Definition		Constraints/numbers
Objective parameters	f_1	Parking fee [yen/hour]	$f_1 < 500$
	f_2	Waiting time [min]	$f_2 < 1.5$
Design parameters	x_1	Basic parking fee [yen/hour]	$500 \leq x_1 \leq 600$
	x_2	Parking position from boarding area [m]	$(R2)50 \leq x_2 \leq 200,$ $(R1)500 \leq x_2 \leq 1000$ $(x_\alpha, x_\beta) = (200{,}500)$
Constant parameters	V_{AGV}	AGV travel speed [m/min].	150

$$f_1(x) = \begin{cases} x_1 & , \quad x_2 \leq 200 \\ x_1 - \min\,(50 + (x_2 - D_{th})/5) \times 10, x_1 \times 0.50), & \quad x_2 \geq 500 \end{cases} \tag{1}$$

$$f_2(x) = 2x_2/V_{AGV} \tag{2}$$



$(\boldsymbol{i})$ $\boldsymbol{\alpha}$: Parking position from boarding/exiting area $\leq \mathbf{200}[\boldsymbol{m}]$

(ii) β : Parking position from boarding/exiting area $\geq 500[m]$

Figure 4. Results of plots by multi-objective optimization

Figure 4 shows the results of the multi-objective optimization plots. An examination of the solutions for α in Table 4 yielded two options for the parking position x_2 at a distance of 50 m from the boarding area. One solution was derived with a non-discounted rate (500 yen per hour), while the other was calculated with a waiting time of 0.667 min, or approximately 40 seconds. These solutions satisfy the constraint condition of "waiting time f_2," which stipulates a maximum waiting time of less than 1.5 min. By contrast, under condition β, the parking position x_2 from the boarding/exiting area is over 500 m, resulting in a waiting time ranging from 6.5 to 8 min. However, several values were derived that offer discounts of up to approximately half the price, depending on the additional distance. Both solutions satisfied the constraint condition of "parking fee f_2." This indicates that a solution exists under both constraint conditions as a result of the separation.

5 DISCUSSION AND CONCLUSIONS

PSS designs that involve multiple stakeholders often fail into compromise initial requirements and constraints because value ranges may not simultaneously satisfy all requirements of stakeholders. To address this issue, this paper proposed a method to support PSS design by integrating TRIZ to the multi-objective optimization process. The application result revealed several practical implications of the method. The view model and MDM are utilized to identify not only the physical contradictions inherent in the PSS structure but also the individual components and their respective dependencies. Additionally, Step 3 aids in understanding the elements that should be considered simultaneously when applying separation. This approach allows for both the partial resolution of physical contradictions and the separation of other attributes potentially affected by the attribute values in question. This capability enables designers to anticipate that fundamental resolution of physical contradictions can be achieved through a comprehensive, top-down design approach for the PSS. Furthermore, by reflecting the results of the separation in the formulation of the objective function according to each constraint condition, we confirmed design solutions that were previously inaccessible. For instance, in Step 5, the separation results informed an optimization process to verify the presence of solutions within the search space. Unlike TRIZ, which is limited to qualitative solution searches, this study facilitates efficient solution searches and the potential for solutions was confirmed by applying an optimization method.

Despite these advantages, some limitations remain. First, the suitability of the separation in Step 4 relies on the designer's perspective and expertise, making it challenging to resolve issues with certainty. Therefore, converting the physical contradiction between functions into a trade-off between requirements or a technical contradiction in the requirement-function DMM can be effective. This allows for the application of the 40 inventive principles to resolve the trade-off from a different perspective. Second, the formulation presented in this paper is simplified. To identify more feasible design solutions, it is essential to further refine the formulation by incorporating more specialized information and optimizing the entire PSS structure, considering its relationship with the objective functions for other requirements. Lastly, the proposed method does not prioritize selecting the solution that maximizes the sum of each required value among those obtained through optimization. Therefore, applying the weighted percent of deviation (WPD) [19], which facilitates the weighting of each objective function in selecting Pareto solutions, may effectively address this issue.

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