

Optimal utility supply network under demand uncertainty for operational risk assessment on a petrochemical industrial park

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Abstract—A two-objective, two-stage mathematical model was developed considering demand uncertainty and operational risk assessment in constructing a utility supply network for steam generation and steam exchange in a petrochemical industrial park. This study defined two objective functions, the total economic cost and risk cost, where the demand uncertainty enhanced the reliability of the utility network design. The economic and risk cost present a holistic study, where the actual operation cost and additional costs in case of industrial operation failure can be determined. For this, two stages were established for both objective functions, a deterministic stage and a stochastic stage. The deterministic stage fixed the parameter values for the optimization problem, while the stochastic stage included the steam supply-demand uncertainty. A case study of the Yeosu industrial park in South Korea was used to show the feasibility of the proposed method, proposing five scenarios for risk assessment analyses. A Pareto set was drawn, showing the optimal values of the optimization scenarios studied. From the optimization analysis, scenario 5 showed the best utility supply network design providing a more realistic network with a balanced total economic cost and risk cost, which presented the lowest risk operation of all facilities. From scenario 5, the results showed a decrease in economic cost by 65.5% to 67.6% compared to the current situation considering the risk costs for the operational risk.

Keywords: Utility Supply Network, Demand Uncertainty, Risk Assessment, Industrial Park, Two-objective Two-stage Stochastic Programming Model

INTRODUCTION

Over the last few decades, industrial parks have been designed for eco-industrial development to provide an operating network that enhances production and minimizes industry losses due to the advantages of exchanging utility resources and turning them into valuable inputs between companies [1-9]. Industrial systems are ruled by the dynamics of demand uncertainty [1,10-15], which influences industry losses and discharge minimization from industries [3,5,16]. Industrial parks have been located in developed countries worldwide. Ulsan, the industrial capital city of South Korea, has an eco-industrial park (EIP) center, representing one primary example of the move towards an industrial symbiotic park concept [1]. Similarly, petrochemical industrial parks have been created in Sweden, such as the Stenungsund petrochemical park [10,12].

Petrochemical industries consist of diverse process plants and utility systems, in which steam is a significant utility stream in the utility supply networks [13,17-21]. Steam is regularly utilized for heat exchange between process plants and utility systems, leading to heat and power integration [15,18,22]. The change in steam production is then easily estimated from a company's facilities (equipment units),

such as boilers, gas turbines, steam turbines, and steam headers [1, 10]. Since the utility network is the core of every industrial energy system, its optimization has been the focus of many studies [23, 24]. Utility network designs are intricate because they require simultaneous optimization of several variables (pressure, temperature, and steam flowrate for multiple complex turbines) and demand uncertainty along with failure risk during system operation. In most industries, a large part of the production cost is the cost of utilities (steam and electricity) required in the process, which depends on the steam demand [20,21,25]. Thus, the utility supply in industrial parks has a significant economic effect in terms of the value of production, operating cost minimization, and demand/supply affected by uncertain conditions [26-30].

Studies in the last decade show the need for research on failure risks of operation in utility supply networks under demand uncertainty conditions, given that the solutions for a combined effect of failure scenarios have not been fully understood (Fig. 1(a)). Scientific publications for the areas of risk assessment and failure risk do not show a steady increase in research on utility supply networks. In contrast, publications implementing demand uncertainty show an increasing interest in research in this area. However, the number of publications has not surpassed 124 in the last decade, supporting the need for more research on utility supply networks, including the concept of demand uncertainty. The significant factors affecting the failure risk encountered in a utility network are decentralized production [31], demand uncertainty [32], rate of techno-

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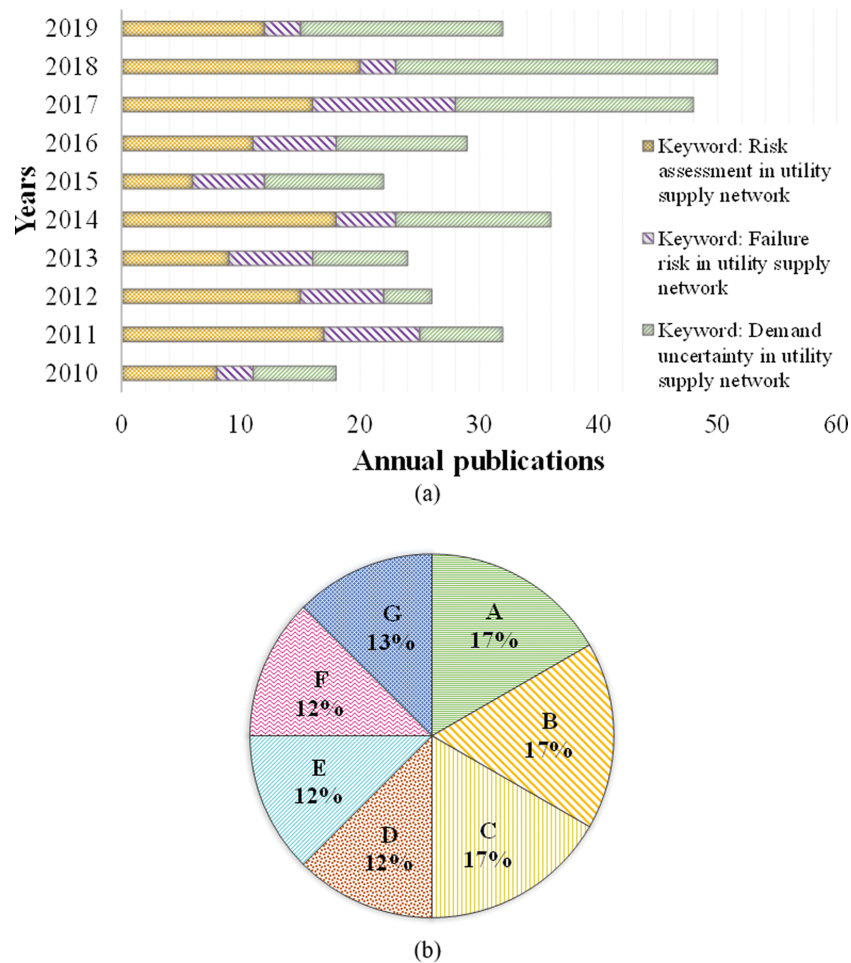


Fig. 1. Development of risk assessment in utility supply networks in the past decade. (a) Annual scientific publications since 2010. Data were extracted from Scopus on 5 March 2020. (b) Factors affecting the risk assessment in utility supply networks. Data were taken from [31-33,35]. A is the demand uncertainty, B is the physical capabilities of pipelines, C is the equipment failure, D is the aging infrastructure, E is the rate of technological change, F is the power system interruption, and G is the decentralized production of utilities.

logical change [32], power system interruptions [33], aging infrastructure [33,34], physical capabilities of pipelines [35], and equipment failure [35] (Fig. 1(b)). The most commonly addressed aspect is demand uncertainty, followed by the physical capabilities of pipelines, and the least often addressed aspect is equipment failure.

Cases wherein utility networks were affected by the failure of the facilities demonstrate the need for a more in-depth evaluation of the equipment capacity variables (discrete variables) [22,36-38] in cases of emergencies (equipment breakdown) and safety accidents [39-42]. Previous studies have analyzed the risk encountered in the operation of the utility network design in different ways, and these affect the overall economic cost of the network. Thus, a risk assessment of accidents was proposed based on the probability of occurrence, where the risk variables were the value at risk, the spectral risk measures, and the expected shortfall [43]. Similarly, another approach developed a risk assessment of the investment efficiency in electric power networks based on the uncertainty of the system reliability [44]. However, there is still a lack of research that considers the economic cost related to the failure risks, such as the reinstallation cost in case of facilities breakdown based on the

uncertainty demand. Therefore, this approach can help with unfolding the trade-off between the economic and risk costs, which can present a contradictory relation and improve sustainability in the industrial park.

A realistic scenario for utility supply networks is a challenging optimization problem caused by the multiple objective functions and uncertainties of utilities supplied throughout operation [4]. Given that two conflicting objective functions may clash with each other by their variables and constraints ranges, their handling would be more troublesome in a single objective function. Hence, multi-objective optimization can be implemented in the way of two objective functions to reach proper operating conditions and avoid a conflict between them, which has been implemented in previous studies [45-48]. In this study, a two-objective two-stage stochastic programming model optimization is proposed to overcome these problems, considering the demand uncertainty and failure risk of operation of a utility supply network. The proposed framework presents two objective functions defined for cost optimization (economic cost and the risk cost) and two stages of the programming model (deterministic and stochastic). The effects of this approach

on failure risk of operation for supplying the steam demand have been thoroughly analyzed. Finally, an operational risk assessment was developed considering the Yeosu industrial park in South Korea as a case study. The rest of this paper is organized as follows: a detailed problem statement is presented in the following section. The mathematical model of the utility supply network section details the defined objective functions and their constraints. The

designed method is discussed in detail, and comparative simulation scenarios are presented in the Results and discussion section. Finally, the conclusions of the study are given.

PROBLEM STATEMENT

This paper considers an optimization programming model based

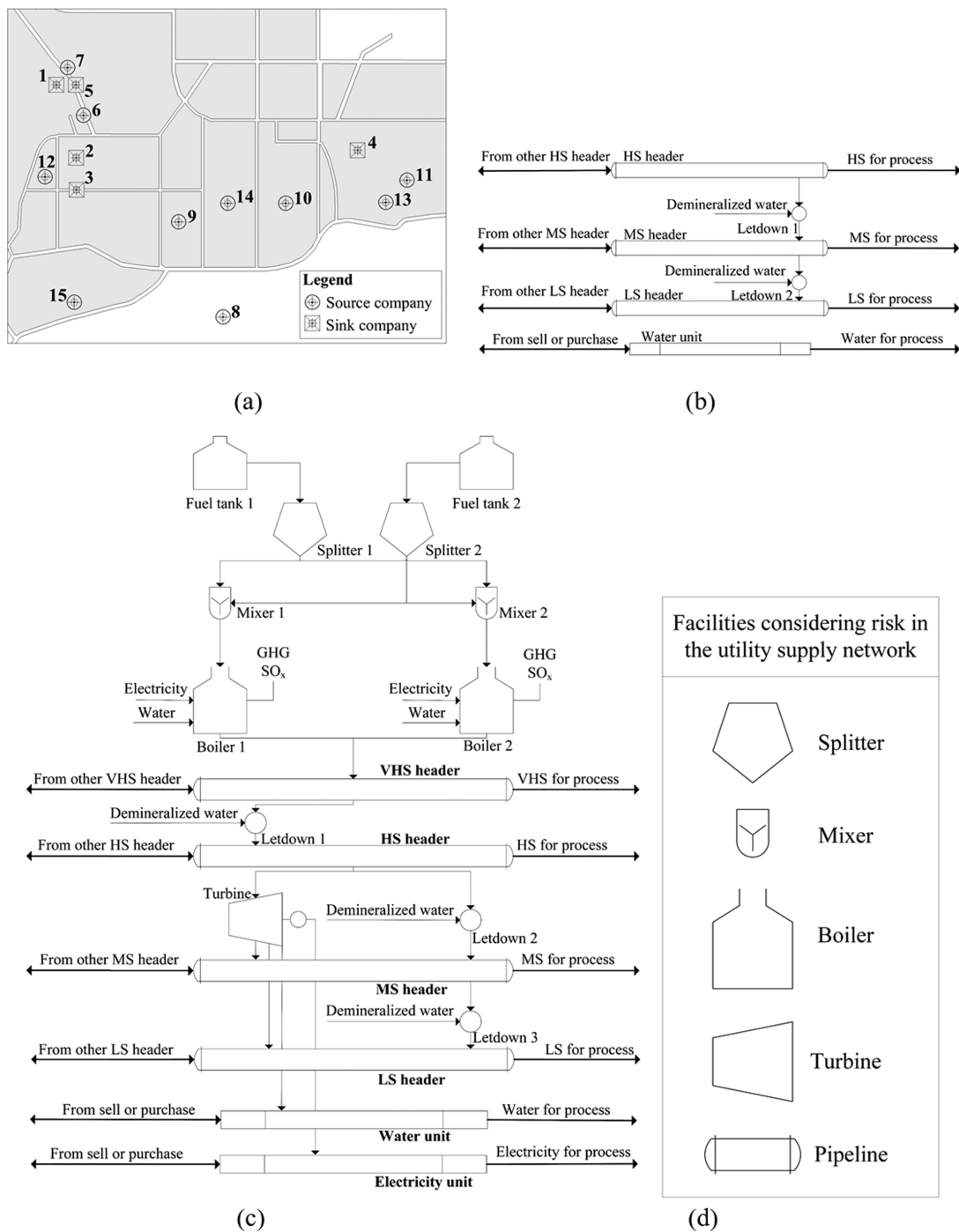


Fig. 2. Configuration of the utility supply network in the case study of the Yeosu industrial park. (a) Map of the industrial park. (b) Utility system in a source company. (c) Process structure in a sink company. (d) Primary facilities for failure risk assessment in a utility process structure.

on the Yeosu industrial park of South Korea. The complex includes two types of companies, source companies, and sink companies, where the source companies produce steam and provide steam to the sink companies, while the sink companies only receive steam. The source companies include power plants (high pressure (HP) steam), chemical factories (a large amount of steam production), and incineration and chemical companies (low marginal cost steam production), while the sink companies include the petrochemical industries [49]. The Yeosu industrial park design (Fig. 2(a)) consists of the sink companies (No. 1 to 5) (Fig. 2(b)), and the source companies (No. 6 to 15) (Fig. 2(c)), which present the base configuration of the companies' locations, which are connected by their utility supply network. Further details are provided in Supplementary Information.

The pipeline network for steam transfer was designed during the construction of the industrial park. However, over the years, the industrial production has varied, while the steam transfer has not been optimized to these conditions. The steam amount generated by companies in the Yeosu utility network has been previously measured for companies like Hansol EME, who recorded the production of medium-pressure (MP) steam of 10 kgf/cm², and KP Chemical, who supplied HP steam of 45 kgf/cm² [1]. Overall, the minimum steam production amount in 2010 was of 3,075 ton/h of very high-pressure (VHP) steam, 514 ton/h of HP steam, and 153 ton/h of MP steam, while the maximum steam production was 3,717 ton/h of VHP steam, 1,172 ton/h of HP steam, and 248 ton/h of MP steam [50]. Thus, the utility supply network has reported profits of 68.52 million dollars per year, while the investment cost was 64.93 million dollars [1].

In this study, data from the source and sink companies were limited to an analysis of the utilities of steam, fuel, water, and electricity for mathematical modeling optimization. The equipment facilities in each company included the fuel tanks (supplying different fuels), the splitters, mixers, boilers, turbines, letdown units for pressure change, the water, and the electricity units. A more detailed description of each equipment facility is presented in the following section on the mathematical model (section 3) and Supplementary Information. The risk assessment integrated into this study consists of an analysis of the potential risk of operation for two main parts of a utility network: the pipeline connections, and the equipment facilities of the companies.

To account for facility failure probability in the analysis, the principal facilities included the boilers, mixers, splitters, and turbines of the companies (Fig. 2(d)). For these, the components of each facility (Table 1) were considered common modes of failure. Here, different cases of failure rate were used in the assumption of an average failure rate for possible interruption of the operation of the facili-

ties in the utility supply network. For a boiler unit, there were considered the superheater, water-wall tubes, air preheater, and fan as principal mechanisms of failure in the boiler. For the turbine, the steam transfer characteristics for the mixer and splitter were used from base records of previous studies [51-55].

1. Algorithm

The two-objective two-stage stochastic model solving algorithm is introduced in Fig. 3. As shown, it is divided into three sections focused on updating the datasets needed from the utility supply network, defining the objective functions and the approaches to utilize, and determining the methodology for the optimization problem. The algorithm description assumes that the utility network problem is solved using mixed-integer linear programming (MILP) [56]. When the demand uncertainty for a supply is considered, the operational variables are identified for different stages to adapt to variations in demand profiles.

The optimization problem includes the simultaneous determination of the optimum economic and risk cost of a utility supply network for optimal operating conditions. When the uncertainty in steam demand and supply is integrated, the design must have the capacity to adapt to varied demand and supply profiles. Therefore, design and operational variables are decided in different stages. This problem is hence addressed as a typical two-stage programming model, which has been widely revised in the literature [11, 36,56,57]. The two-stage stochastic programming classifies the variables as a first stage variable (deterministic stage) and the second stage (stochastic stage) for determining the uncertainty parameters, which allows defining a more realistic design [57]. The optimization process is developed iteratively with values of uncertain demand for the utility supply. Referring to the law of large numbers, the average of results is obtained from a large number of trials that are close to the expected value [56]. In this study, the advantages of using the stochastic model and the deterministic model are based on common metrics for the defined objective functions.

1-1. Section I. Target System Configuration

Section I of the program was focused on the data collection of materials cost and failure rates for the equipment units and pipeline connections of the industrial park. It was assumed that the main components for steam production, such as the boilers, turbines, splitters, and mixers were the most relevant units to account for during optimization programming. Furthermore, the base conditions of the industrial park were adopted from a previous study [49], and they include the mass balances of the processes for the utility network.

1-2. Section II. Model Development

Section II establishes the approach methodologies for the two defined objective functions. Here, it is detailed the deterministic

Table 1. Failure rate of the facilities in the utility supply network

Equipment	Description	Average failure rate	Unit	Reference
Boiler	Closed vessel which generates the steam	9.00E-07	/ h	[53]
Splitter	Redistribute the feed stream depending on specified condition	6.54E-08	/ h	[49]
Turbine	Rotary mechanical devise that extracts energy from steam	1.87E-05	/ h	[50]
Mixer	mechanical devise that mix different feed streams	7.95E-07	/ h	[49,51]

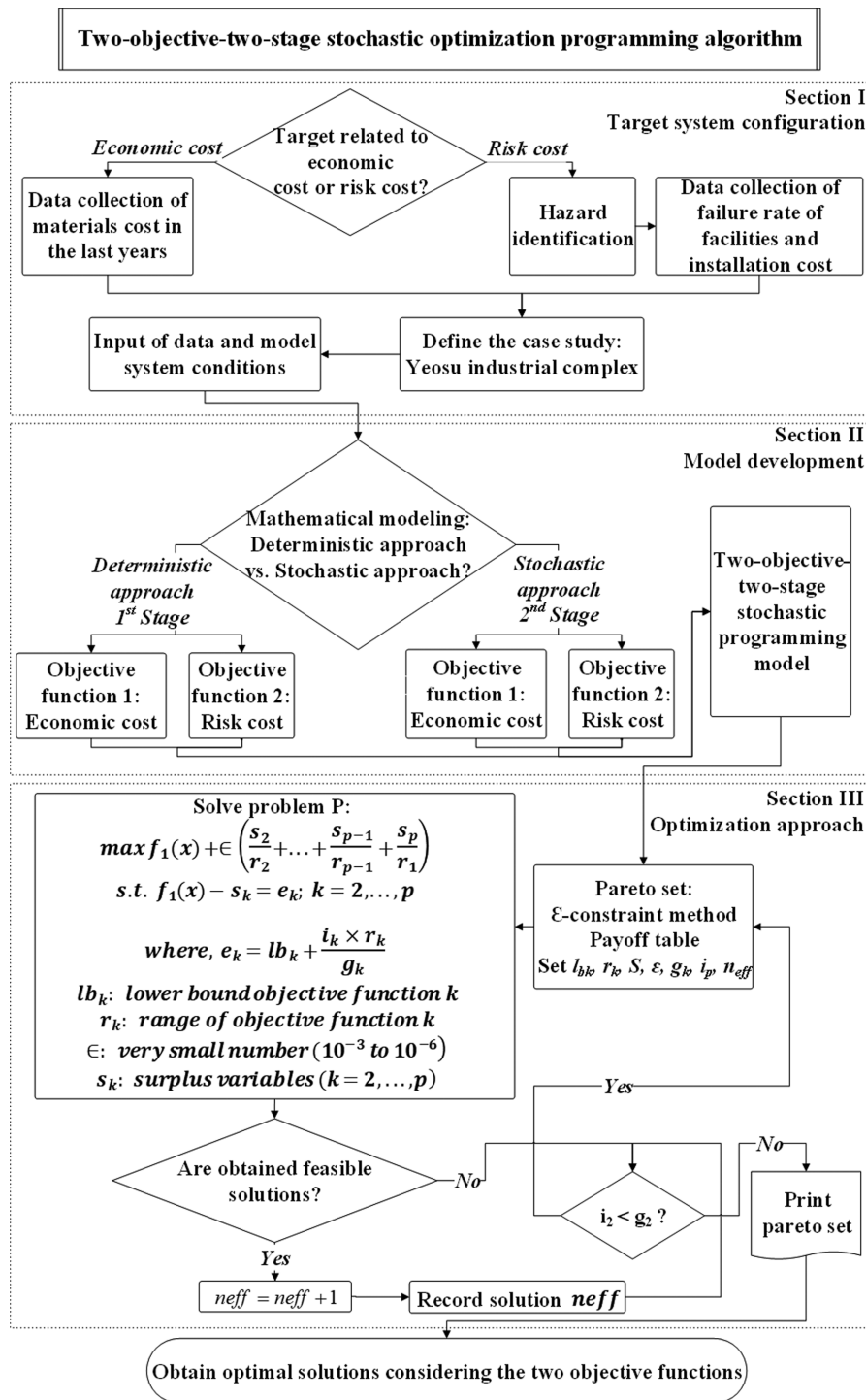


Fig. 3. Block-flow diagram of the devised two-stage model-solving algorithm with the abounding procedure.

stage and stochastic stage for both the economic cost and risk cost of the programming model for the utility supply network (Table 2). The first objective function includes the total investment cost of the utility network based on the distance between companies, the operating cost, and the materials cost of the utility supply network. The second objective function groups the failure risk metrics based on the pipeline connections and the equipment facilities (boilers, turbines, splitters, and mixers).

Furthermore, the two-stage stochastic programming model is presented with a deterministic model optimization in the first stage for minimizing the investment costs of the utility supply network. In this stage, both objective functions account for fixed values for optimization. For the risk cost, the integration of the pipeline connections cost is included in the deterministic stage of this function. The second stage involves stochastic model optimization to include the demand uncertainty of steam supply and a later risk

Table 2. Summary of the mathematical models for the two-objective functions in the two-stage stochastic optimization

Objective function	Stage	Description (highlights)
Economic cost	Deterministic	<ul style="list-style-type: none"> The investment cost is fixed, considering the connections between pipelines for steam transfer in the utility network. The operating cost is fixed by the connections of the installed pipelines between companies.
	Stochastic	<ul style="list-style-type: none"> The operating cost depends on the varied steam demand of each company in different demand scenarios. The raw cost of materials (fuel, water, and electricity) is integrated as a variable based on the market cost increase in the last years.
Risk cost	Deterministic	<ul style="list-style-type: none"> The failure risk is dependent on the connection between pipelines for steam exchange. The steam transfer is based on the distance between companies.
	Stochastic	<ul style="list-style-type: none"> The failure risk of facilities (turbine, boiler, splitter, and mixer) is correlated to the steam demand. The total operation risk failure of the facilities is considered together.

cost optimization. Here, the economic cost is defined by the uncertain demand calculation of the optimal operating conditions for a real system. For the risk cost, the facility failure risk is accounted for in the second stage.

1-3. Section III. Optimization Approach

The optimization approach is considered in Section III by the ε -constraint method, which is an iterative methodology where the optimum solution to the objective functions is defined after several trials, leading to a Pareto set plot for determining multiple points of solutions for both objective functions. The chosen objective function range of the target values for decision-making is defined by the set of Pareto optimal solutions. The trade-off relationship identifies numerous solutions. These solutions represent the best compromises among multi-objectives. Finally, these results are analyzed through a comparison to obtain an optimal solution overall.

MATHEMATICAL MODEL

A mathematical model is proposed to integrate the economic cost with the failure risk of operation of all the companies in the industrial park. Two objective functions, which consist of total economic cost and risk cost, were used to optimize the utility supply network. Here, demand uncertainty was considered in both objective functions, and operation failure of the companies was integrated into the risk cost to approach to a more realistic utility supply network design. During the optimization process, the companies' utility demand must be satisfied. General mass balance equations in the utility network system are defined from previous studies [49] for all the main equipment units in the companies.

1. Two-objective Two-stage Stochastic Programming Model

The objective functions in this study intend to optimize a utility supply network by minimizing the total economic cost and risk cost. A two-stage stochastic programming approach (Eq. (1)) included the demand uncertainty for a real scenario, namely the utility supply network in the Yeosu industrial park. This approach integrates two types of parameters and variables related to the deterministic ($Total_{Cost, first stage}^{Economic}$ and $Total_{Cost, first stage}^{Risk}$) and stochastic

$$(\sum_s (p(s) \times Total_{Cost, second stage}^{Economic}) \text{ and } \sum_s (p(s) \times Total_{Cost, second stage}^{Risk}))$$

approach methodologies of programming. The second stage integrates the steam demand uncertainty, where $p(s)$ is assumed to be the inverse of the sum of demand scenarios (s).

$$\text{Min} \begin{cases} Total_{Cost, first stage}^{Economic} + \sum_s (p(s) \times Total_{Cost, second stage}^{Economic}) \\ Total_{Cost, first stage}^{Risk} + \sum_s (p(s) \times Total_{Cost, second stage}^{Risk}) \end{cases} \quad (1)$$

1-1. First Objective Function and the First Stage

The total economic cost of the first stage ($Total_{Cost, first stage}^{Economic}$) presented in Eq. (2) is composed of the investment cost ($Cost_{i, i', sh, steam}^{invest}$) and the operating cost ($Cost_{i, i', sh, steam}^{oper}$). In the first stage (deterministic), the investment cost is considered based on the installation of the pipeline between companies, while the operating cost represents the maintenance cost of the pipelines for steam transfer. Fixed parameter values were defined for this stage in the mathematical model of Eq. (2), considering no variations based on the demand scenario. Here, the investment and operating costs are proportional to the pipeline length, given that these variables are directly related to the distance between companies ($Dist_{i, i'}$).

$$Total_{Cost, first stage}^{Economic} = \sum_i \sum_{i'} \sum_{sh} \sum_{steam} [Cost_{i, i', sh, steam}^{invest} + Cost_{i, i', sh, steam}^{oper}] \quad (2)$$

The total investment cost ($Cost_{i, i', sh, steam}^{invest}$) and fixed total operating cost ($Cost_{i, i', sh, steam}^{oper}$) account for the capital cost of the utility supply network, which are shown in Eqs. (3) and (4), respectively. The investment cost represents the installation of pipeline connections between companies, and it is a function of the fixed investment cost parameter (FC^{invest}) by the binary variable of steam transfer ($b_{i, i', sh}^{steam}$). The operating cost depends on the fixed operating cost parameter (FC^{oper}), as well as the distance between companies ($Dist_{i, i'}$) (Eq. (4)).

$$Cost_{i, i', sh, steam}^{invest} = (FC^{invest} b_{i, i', sh}^{steam} + VC^{invest} b_{i, i', sh}^{tr}) Dist_{i, i'} / DP \quad (3)$$

$$Cost_{i, i', sh, steam}^{oper} = FC^{oper} b_{i, i', sh}^{steam} Dist_{i, i'} \quad (4)$$

1-2. First Objective Function and Second Stage

In the second stage (stochastic), the scenario-based description of demand uncertainty is defined for the total economic cost of the second stage ($Total_{Cost, second stage}^{Economic}$) (Eq. (5)). The operating cost of the second stage ($Cost_{s, i, i', sh, steam}^{oper}$) depends on the varied steam

demand for each company based on the parameter VC^{oper} , and the binary variable of steam transfer ($bi_{s,i,i',sh}^{tr}$), which shows the variation of steam transfer for various demand scenarios (Eq. (6)).

$$\text{Total}_{\text{Cost, second stage}}^{\text{Economic}} = \sum_s \left[\sum_i \sum_{i'} \sum_{sh} \sum_{steam} \text{Cost}_{i,i',sh,steam}^{oper} + \sum_i \text{Cost}_i^{\text{Raw}} \right] \quad (5)$$

$$\text{Cost}_{s,i,i',sh,steam}^{oper} = VC^{oper} bi_{s,i,i',sh}^{tr} \text{Dist}_{i,i'} \quad (6)$$

The raw cost is known to fluctuate based on the market variations for materials, including fuel, water, and electricity (Eq. (7)). Here, it was considered the price of fuel in the last few years (Pri^{fuel}), the amount of fuel consumed by the companies in the utility network ($A_{s,i,boil,"con"}^{\text{fuel}}$), the industrial water price ($\text{Pri}^{\text{water}}$), the amount of industrial water being consumed by the companies ($A_{s,i,wu,"con"}^{\text{water}}$), the electricity price (Pri^{elec}), and the amount of electricity utilized by the companies ($A_{s,i,"con"}^{\text{elec}}$).

$$\text{Cost}_{s,i}^{\text{Raw}} = \sum_{boil} \sum_{fuel} \text{Pri}^{\text{fuel}} A_{s,i,boil,"con"}^{\text{fuel}} + \sum_{wu} \sum_{water} \text{Pri}^{\text{water}} A_{s,i,wu,"con"}^{\text{water}} + \text{Pri}^{\text{elec}} A_{s,i,"con"}^{\text{elec}} \quad (7)$$

1-3. Second Objective Function and the First Stage

In the deterministic stage, the risk cost related to the pipeline connections failure probability is fixed to a single demand scenario. This assumption was implemented in the system based on the physical limitations for the construction of pipeline connections in the industrial park. The total risk cost in the first stage ($\text{Total}_{\text{Cost, first stage}}^{\text{Risk}}$) is calculated by multiplying the operation failure risk of pipelines ($\text{Risk}_{i,i'}^{\text{pl}}$) and the installation cost of the pipelines (C^{pl}) (Eq. (8)). Further, $\text{Risk}_{i,i'}^{\text{pl}}$ results from the multiplication of the failure rate of pipelines (fail^{pl}), the binary variable of steam exchange between companies ($bi_{i,i',sh}^{\text{steam}}$), and the distance between companies ($\text{Dist}_{i,i'}$) (Eq. (9)).

$$\text{Total}_{\text{Cost, first stage}}^{\text{Risk}} = \sum_i \sum_{i'} C^{\text{pl}} \text{Risk}_{i,i'}^{\text{pl}} \quad (8)$$

$$\text{Risk}_{i,i'}^{\text{pl}} = \sum_i \sum_{i'} \sum_{sh} \text{fail}^{\text{pl}} \times bi_{i,i',sh}^{\text{steam}} \times \text{Dist}_{i,i'} \quad (9)$$

1-4. Second Objective Function and Second Stage

The risk cost stochastic stage aims to extend the utility supply network design to a realistic scenario. For this, the risk cost in the second stage ($\text{Total}_{\text{Cost, second stage}}^{\text{Risk}}$) considers the operation of facilities in the source companies. Since facility operation is directly related to the steam demand, the operation risk cost of the facilities is considered based on demand scenarios. The risk cost is calculated by summing the products of the installation cost of the different facilities (C^{boil} , C^{tur} , C^{spl} , and C^{mix}) and their respective failure risks ($\text{Risk}_{s,i}^{\text{boil}}$, $\text{Risk}_{s,i}^{\text{tur}}$, $\text{Risk}_{s,i}^{\text{spl}}$, and $\text{Risk}_{s,i}^{\text{mix}}$) (Eq. (10)).

$$\text{Total}_{\text{Cost, second stage}}^{\text{Risk}} = \sum_s \sum_i \left[C^{\text{boil}} \text{Risk}_{s,i}^{\text{boil}} + C^{\text{tur}} \text{Risk}_{s,i}^{\text{tur}} + C^{\text{spl}} \text{Risk}_{s,i}^{\text{spl}} + C^{\text{mix}} \text{Risk}_{s,i}^{\text{mix}} \right] \quad (10)$$

It is assumed that the boiler, turbine, splitter, and mixer are (i) the main equipment units at the source companies that may fail during operation and (ii) the principal components for steam production and consumption. Eqs. (11) to (14) show the risk of failure at source company facilities. The risk of failure results from

multiplying the failure rate of facilities ($\text{fail}^{\text{boil}}$, fail^{tur} , fail^{spl} , and fail^{mix}) by the binary variable of facilities operation ($\text{br}_{s,i,boil,steam}^{\text{oper}}$, $\text{br}_{s,i,tur,steam}^{\text{oper}}$, $\text{br}_{s,i,spl,fuel}^{\text{oper}}$, and $\text{br}_{s,i,mix,fuel}^{\text{oper}}$).

$$\text{Risk}_s^{\text{boil}} = \sum_{boil} \sum_{steam} \text{fail}^{\text{boil}} \times \text{br}_{s,i,boil,steam}^{\text{oper}} \quad (11)$$

$$\text{Risk}_s^{\text{tur}} = \sum_{tur} \sum_{steam} \text{fail}^{\text{tur}} \times \text{br}_{s,i,tur,steam}^{\text{oper}} \quad (12)$$

$$\text{Risk}_s^{\text{spl}} = \sum_{spl} \sum_{fuel} \text{fail}^{\text{spl}} \times \text{br}_{s,i,spl,fuel}^{\text{oper}} \quad (13)$$

$$\text{Risk}_s^{\text{mix}} = \sum_{mix} \sum_{fuel} \text{fail}^{\text{mix}} \times \text{br}_{s,i,mix,fuel}^{\text{oper}} \quad (14)$$

2. Mass Balance in the Utility Supply Network

A material balance method defined the constraints of the system and to represent the utility supply network. This method assumes the operability of the network at a steady-state, where there is no loss of materials in the steam exchange. Eqs. (15) and (16) represent the material balance equations for the whole utility supply network. Here, $D_{s,i}^{\text{mat}}$ is the demand for materials in the network, $A_{s,i, \text{fac}, st}^{\text{mat}}$ is the amount of materials transferred by facilities, and $E_{s,i, \text{fac}, st}^{\text{mat}}$ is the materials exchange by facilities. The materials are the fuel, water, and electricity transferred between facilities. The different demand scenarios are represented as s , by each company i . The facilities (fac) are defined as the fuel tank, splitter, mixer, boiler, turbine, letdown unit, water unit process, and pipeline.

The state (st) refers to the input or output of material from the facility where it is consumed or generated. A more detailed description of each variable is presented in the nomenclature. Eq. (15) represents the amount of material in the facilities of any company that should meet its demand under the demand scenario condition. Eq. (16) shows the total amount of exchanged material in the facilities, which should be equal to the original amount of material in the facilities. More details related to the mass balance for each facility are presented in Supplementary Information, and a deeper understanding can be found in previous studies [26,49].

$$D_{s,i}^{\text{mat}} \leq A_{s,i, \text{fac}, st}^{\text{mat}} \quad (15)$$

$$A_{s,i, \text{fac}, st}^{\text{mat}} = \sum_{\text{fac}} E_{s,i, \text{fac}, st}^{\text{mat}} \quad (16)$$

RESULTS AND DISCUSSION

The proposed two-objective two-stage stochastic model was applied to the Yeosu industrial park. The work was developed in the software GAMS (General Algebraic Modeling System) v24.6, which utilizes the CPLEX solver [58]. The designed model implemented a series of variables and equations for optimizing the total economic cost and the total risk cost, representing the realistic scenario of an industrial park for assessing the most optimal operation. Five scenarios were conducted for operational risk assessment (Table 3), a base case (scenario 1), an optimized base case (scenario 2), a stochastic optimized case (scenario 3), a two-objective two-stage stochastic optimized case with the integration of the operation risk of pipelines (scenario 4), and a two-objective two-stage stochastic case with integration of the operation risks of all the facilities (scenario 5). The base case outlines the utility supply network optimization based on a multi-period deterministic model

Table 3. Description of case studies for the optimization problem

No.	Scenario	Description
1	Base case	Base utility network by deterministic approach.
2	Optimized base case	Economic cost optimization by deterministic approach.
3	Stochastic optimized case	Economic cost optimization by stochastic approach (demand uncertainty).
4	Two-objective two-stage stochastic optimized case with integrated operation risk of pipelines	Economic cost and pipeline risk cost optimization by stochastic approach (demand uncertainty).
5	Two-objective two-stage stochastic case with integrated operation risks for all facilities	Economic cost and risk cost optimization for the whole utility supply network by a stochastic approach (demand uncertainty).

Table 4. Comparison of economic cost and risk cost of optimized utility network for each scenario

No.	Scenario	Economic cost [\$/year]	Risk cost [\$/year]
1	Base case [49]	276,461,500	-
2	Optimized base case	89,683,480	-
3	Stochastic optimized case	89,698,130	-
4	Two-objective two-stage stochastic optimized case with integrated operation risk of pipelines	589,439,300	473,184
		(High)	(Low)
		89,683,478	3,641,736
		(Low)	(High)
5	Two-objective two-stage stochastic case with integrated operation risks for all facilities	95,461,527	5,362,764
		(High)	(Low)
		89,683,478	7,543,536
		(Low)	(High)

from previous research [44]. Scenario 2 illustrates the optimized utility supply network with updated materials cost values for inversion costs. Scenario 3 shows the economic cost integrated with demand uncertainty. Scenario 4 merges the risk cost of pipelines into the optimization model. Scenario 5 illustrates the full two-stage stochastic model that evaluates the economic cost and risk cost of the pipelines and facilities for the companies.

The results from all scenarios show the different economic costs and risk costs of the utility supply network (Table 4). Analyses of the five scenarios address the economic cost and risk cost; the more significant difference in the results between the base case and the subsequent scenarios shows the improvement provided by the optimization model. The results of the scenario 2 show a \$186,778,020 (67.5%) decrease in the total economic cost compared to the base case. The reasonable implication of this is that the current utility network model (base case) is not suitable for the current actual price of raw materials. Scenario 3 presents a \$186,763,370 decrease in the total economic cost compared to the base case, but a \$5,650 (0.02%) increase compared to case study 2. The results of scenario 4 show a dramatic increase of \$499,741,170, by 6.5-times the total economic cost of scenario 3 for the highest economic cost determined at the lowest risk cost calculated, which suggests that the risk cost affected the minimization of the economic cost.

Further, the lowest total economic cost of the scenario 4 shows a \$14,652 (1%) decrease compared to the scenario 3. Here, the risk cost increased as \$3,168,552 by 6.7-times due to a \$499,755,822 (84.8%) decrease in the economic cost. The results of scenario 5 present a \$490,977,773 (92%) decrease for the highest total eco-

nomical cost determined as compared to scenario 4. In contrast, the lowest total economic cost shows no variation compared to scenario 4. These suggest that the risk cost greatly influenced the optimization problem for decreasing and maintain the total economic cost. Overall, the companies in the utility supply network design were able to meet their steam demand.

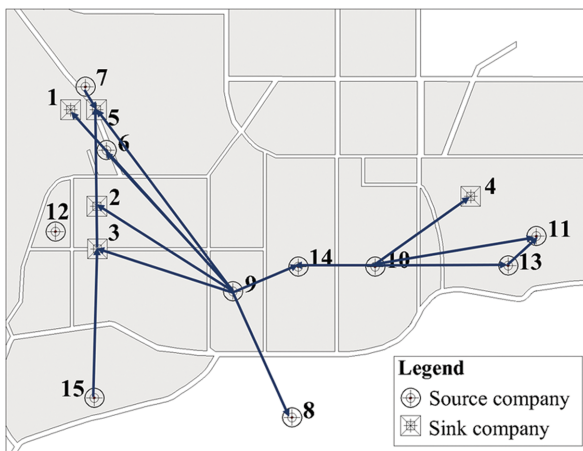
1. Base Case and Optimized Base Case

Scenario 1 is the base case from a deterministic model in which the optimization problem is treated by multi-season variation, based on previous research proposed by [49]. Here, the seasonal variation accounts for the different steam demand amounts required by the petrochemical industrial park. The base case integrates the previous conditions of the industrial complex, considering past cost values for each material tracked in the utility supply network. The estimated past economic cost of this case was of 276 million dollars. This design sought to meet the steam delivery based on the seasons of a year. Furthermore, scenario 2 is the optimized base case, which implements the concept of seasonal variation with an update to present conditions of investment costs (Table S4), for a correct estimation of the economic cost. Scenario 2 past economic cost was estimated to be 89 million dollars. A detailed explanation of the scenarios 1 and 2 is provided in Supplementary Information.

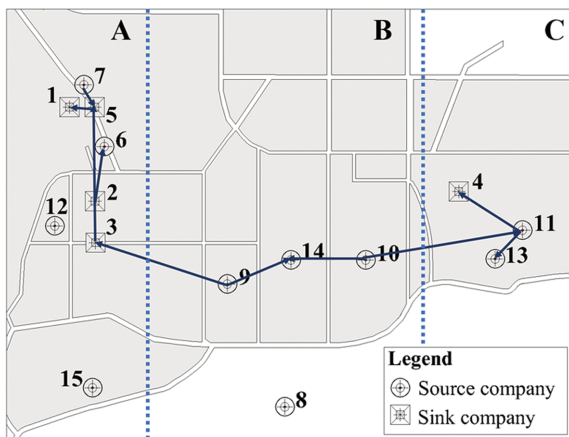
2. Stochastic Optimized Case

Scenario 3 is the stochastic optimized case, which utilizes a stochastic model to include the demand uncertainty of steam in the economic cost optimization. The economic cost was estimated to be around 89 million dollars (Table 4), indicating a slight increase compared to the optimized base case. The optimized utility sup-

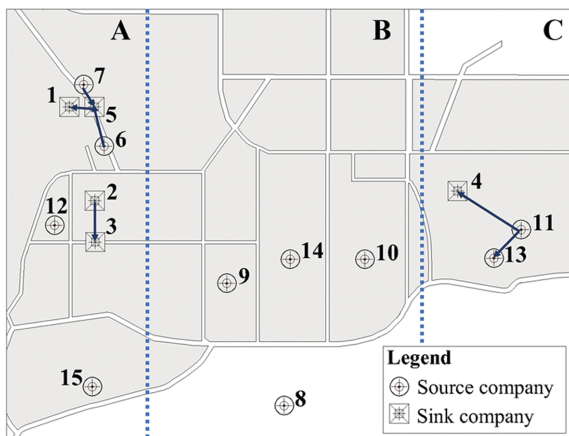
ply network design experiencing demand uncertainty shows that companies 9 and 10 are the principal steam producers (Fig. 4(a)).



(a)



(b)



(c)

Fig. 4. Schematic diagram of the utility supply network of scenarios 3 and 4. (a) Design for optimized utility supply network of scenario 3 considering demand uncertainty. (b) Design for minimization of the total economic cost for optimized utility supply network of the scenario 4. (c) Design for minimization of the risk cost for optimized utility supply network of scenario 4.

The devised optimization methodology could represent the demand uncertainty as well as the conditions of demand scenarios. However, it was not able to minimize the economic cost of the utility network compared to the optimized base case. Although scenario 3 maintains an economic cost similar to the previous scenario, the design provides further analysis of demand uncertainty in the following optimization scenarios.

3. Two-objective Two-stage Stochastic Optimized Case with Integrated Operation Risk of Pipelines

Scenario 4 is the two-objective two-stage stochastic optimized case with integrated operation risk of pipelines. This case employs a stochastic model for including the demand uncertainty and the terms of risk failure into the economic cost and risk cost optimization. In the design for minimization of total economic cost for the optimized utility supply network, the design shows that the companies are centrally distributed by their steam production-exchange (Fig. 4(b)). The centralized distribution turns the source companies into sink companies, except for companies 9 and 10. The sink companies only satisfy their steam demand through the exchange with source companies. Since steam exchange is cheaper than the generation of steam from each company for self-sufficiency, the distribution design requires the initialization of the cost of pipelines between companies. The centralization design of the utility supply network causes the minimization of the economic cost in the scope of the whole industrial park. Furthermore, given that in scenario 4 the risk of operation of pipelines was considered, the installed pipelines between companies for centralized distribution integrated the failure rate of facilities in the design. Therefore, the economic cost decreased while the risk cost increased, illustrating a trade-off between both objective functions.

Furthermore, for this scenario, three areas (A, B, and C) were defined for the analysis of the economic cost based on the clusters formed for steam supply and their primary producer companies. Area A includes companies 1, 2, 3, 5, 6, 7, 12, and 15, area B contains companies 8, 9, 10, and 14, and area C involves companies 4, 11, and 13. Most of the companies in area A are connected, except for companies 12 and 15, which act as self-sufficient companies (supply their steam demand). Supplying steam to the source companies, companies 2 and 5 act as producer companies in this area, where company 2 generally supplies the steam to companies 3, 5, and 6. In area B, companies 9 and 10 are supplying steam to companies 3 and 14, and 11, respectively, while company 8 operates as a self-sufficient company. Companies 9 and 10 serve as steam supplier companies. Companies in area C are fully interconnected, showing that company 11 is the only producer company, supplying to companies 4 and 13. A higher steam exchange is shown in this configuration (Fig. 4(b)), as five companies act as the main suppliers, lowering the costs of steam generation. However, this design is prone to a higher failure risk probability because the steam exchange is centrally distributed by the major supplier companies.

On the contrary, a utility supply network design where companies are locally distributed is presented (Fig. 4(c)). In this design, the utility supply network is utterly decentralized. This design minimizes the installation of pipelines between sink and source companies to minimize the total risk cost. Accordingly, all source companies should generate steam to meet their steam demand, which is called

self-sufficiency. Although self-sufficient companies reduce the failure risk of facilities of the industrial park, it also maximizes the total economic cost. Here, to minimize the total risk cost, only some sink and source companies are connected to exchange steam from source to sink companies. In areas A and C, companies 2, 5, 6, 7, and 11 act as supplier companies to the sink companies 1, 3, 4, and 5. The rest of the companies (8, 9, 10, 14, and 15), mainly in the area B, act as self-sufficient. With this approach, the pipeline connections are reduced by increasing the self-sufficient companies, and the risk cost decreased compared to the centrally distributed scenario (Fig. 4(b)).

4. Two-objective Two-stage Stochastic Case with Integrated Operation Risk for All Facilities

Scenario 5 is the two-objective two-stage stochastic case that accounts for the operational risks of all facilities, including boiler, turbine, splitter, and mixer, as well as pipelines. Note that this case is a more realistic scenario of a fully functional utility supply network in the target industrial park. The mixer, splitter, boiler, and turbine units are assumed to represent the principal failure risks of the companies. In summary, the optimization result of the risk cost and the total economic cost is shown in a Pareto set in Fig. 5. The Pareto result of this scenario is divided into three parts: high risk, optimal cost set, and high cost set. The first three points of the Pareto set are grouped as a high-risk set, leaning more to the risk cost. A change of slope is observed between points 3 and 4, showing a change in the total economic cost and risk cost. The optimal cost set occurs between points 4 and 7, where the risk cost and total economic cost shows an almost linear inverse relation. Lastly, the economic cost dramatically increases until point 8 (high cost set). Therefore, the Pareto set helps in understanding more directly the relations of operational cost for this utility supply network. In this way, the optimization decision is easier to find, allows more ranges for decision making when considering more important one cost over the other, and enhances the speed of the

decision-making process, as it is not directly linked to the expertise of a third party to verify each calculation of the optimization.

Point 4 in the Pareto set presents an economic cost of around 90 million dollars and a risk cost of 6.5 million dollars. Point 5 shows values of 90.85 million dollars for the economic cost and 6.3 million dollars of risk cost. Point 6 shows 91.29 million dollars of economic cost and 6 million dollars of risk cost, which are approximately the same as point 7 values (91.92 million dollars of economic cost and 5.67 million dollars of risk cost). Given the small variation in optimal values, this area was taken for risk analysis using an average value of economic cost and risk cost.

In the high-risk set, the utility network design for point 1 shows that the steam is primarily produced by companies 9, 10, 13, and 15 (Fig. 6(a)). Since point 1 represents an extreme case to minimize the total economic cost, this design presents a centrally distributed utility network, where most of the companies' supply is provided by a few companies. Except for the steam supplier companies, the rest of the companies are considered as sink companies, including non-activating source companies, which satisfy their steam demand by the steam exchange. Accordingly, the steam exchange by the centralized distribution of the utility supply network lowers the total economic cost slightly more than the self-sufficiency. However, centralized distribution increases the risk cost, given the longer pipeline connections between companies.

In the optimal cost set, the utility supply network design is centralized, similar to the high-risk set. Company 3 supplying to 1 and 5, and company 9 supplying to 12 are added to the utility network design developed in point 5 from the Pareto set (Fig. 6(b)). This design shows a close network (as previously shown in point 1) by also removing the connection between companies 13 and 11, and 15 and 5. The utility supply network shows a full connection between companies for the case of the total minimized risk of point 8 (Fig. 6(c)). Steam transfer between companies 10 to 7, 1 to 7, 7 to 6, 5 to 1, 9 to 15, 14 to 15, and 13 to 4 is added in this

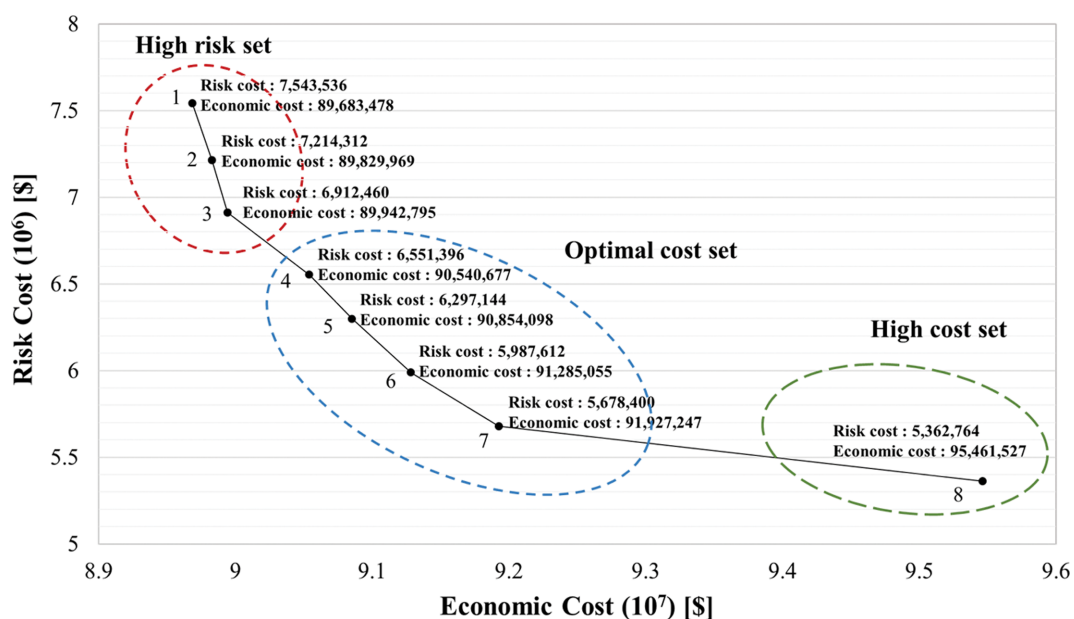


Fig. 5. Pareto set for the economic cost and risk cost from the scenario 5.

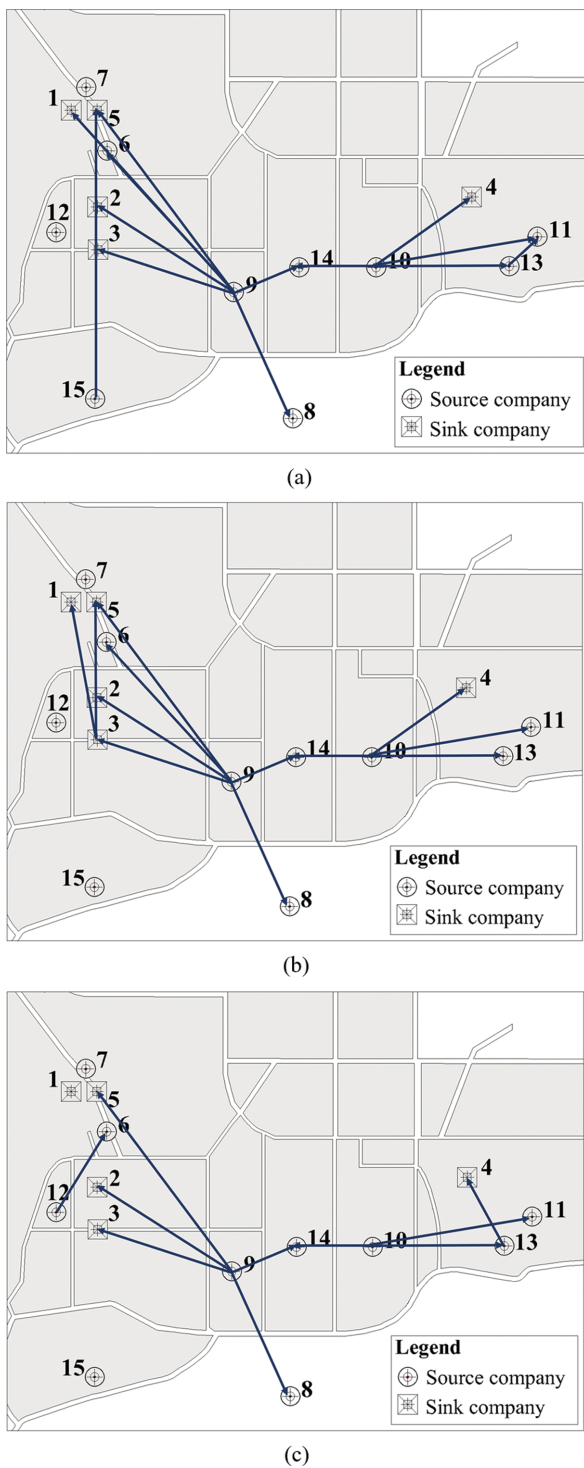


Fig. 6. Comparison of the pipeline network of case studies for the main Pareto set points. (a) Pareto point 1 in the high risk cost set. (b) Pareto point 5 in an optimal cost set. (c) Pareto point 8 in the high economic cost set.

design, which helps to reduce steam. Furthermore, the steam transfer (points 1, 5, and 8) is principally conducted by companies 9 and 10 (Table 5), where companies 15 to 5, and 9 to 1 exchange steam, which places them in the high risk set for being far from

each other.

Comparing the utility supply network with the lowest risk cost from the scenario 4 (Fig. 4(c)) with the scenario 5 (Fig. 6(c)), the latest scenario achieves a more realistic configuration by changing the network design from locally distributed to fully connected. Scenario 5 assesses the risk of all operating facilities. Although the risk cost from the scenario 4 is lower than that from the scenario 5, the economic cost increases in the locally distributed network design. The improved network from the scenario 5 has longer connections and provides a more realistic utility supply network, showing a balanced total economic cost and risk cost. Therefore, a full design, in reality, includes the risk operation of all facilities in the utility supply network which allows a better approach for the optimization of total economic cost, risk cost, and a risk assessment of the system as well.

On the other hand, the steam exchange maintains the central distribution in which few major companies supply steam for achieving the lowest total economic cost in scenario 4 (Fig. 4(b)) and scenario 5 (Fig. 6(a)). Scenario 4 shows a network where companies 9 and 10 are major companies, which is the same as scenario 5 does. The utility networks maintain this characteristic in their design. Thus, the central distribution of companies is essential for minimizing economic cost. Further, the economic cost values in both case studies are the same. Although the pipeline connections in scenario 5 increase, the realistic configuration presents an equilibrium for both, the total economic cost and risk cost of the utility network. Scenario 5 adequately addresses a real industrial park operation for an optimized utility supply network.

CONCLUSIONS

A two-objective, two-stage stochastic model was developed to assess the risk of operation for an optimal solution in an industrial park. Objective functions were defined based on the investment cost of the materials, the operational failure risk of facilities in the companies, and the demand uncertainty. The economic cost and risk cost were divided into two stages based on the deterministic and stochastic terms of the optimal design of the utility supply network. Five scenarios were evaluated and compared with the current case and each one of the deterministic and stochastic scenarios at the Yeosu industrial park of South Korea.

Previous research on optimization of utility networks in the industrial park focused on a periodically variant multi-scenario, which is particularly unfeasible due to the difficulties and economic losses of building different types of pipeline networks for each scenario. Demand uncertainty and operational risk assessment were implemented into the objective functions using a stochastic mathematic formulation, which allowed a more realistic utility network design. The proposed mathematical model was able to integrate the deterministic and stochastic stages of the economic cost and risk cost of the utility network.

Different scenarios were defined to find a realistic optimal utility supply network design. The utility supply network included the risk operation of key facilities in the risk cost (scenarios 4 and 5). Pipeline failure was found to cause problems related to central distribution and local distribution of the steam exchange between com-

Table 5. Comparison of pipeline network case studies of (a) Pareto point 1 in the high risk cost set, (b) Pareto point 5 in the optimal costs set, and (c) Pareto point 8 in the high economic cost set

		To														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
From	1							c					Sink company			
	2												Source company			
	3	b				b							a: High risk set			
	4												b: Optimal cost set			
	5	c						c					c: High cost set			
	6					b										
	7															
	8															
	9	a	a, b, c	a, b, c		a, b, c	a, b	a	a, b				b, c		a, b, c	
	10				a, b				c			a, b, c		a, b, c	a, b	
	11															
	12							c								
	13											a				
	14															
	15			b		a									c	

panies, for which the risk probability of facilities in the companies was included in the mathematical model. Here, the turbine and boiler showed a particularly negative effect on the operation status of the companies. These facilities presented high failure risk, resulting in a centrally distributed utility network. This concluded that the risk cost of the utility supply network tends to be regionalized in the network design, and this should be considered when developing a reliable supply network.

In comparison with the results from the base case, the proposed two-objective two-stage stochastic model (scenarios 5) showed the best realistic network design for the operation of a utility supply network. The highest economic cost and the lowest economic cost were reduced by 65.5% and 67.6%, respectively. Thereby, the model can be used to optimize the operation strategy for companies under demand uncertainty to achieve a sustainable and reliable utility supply network in a petrochemical complex.

Notably, this study primarily focuses on the steam utility supply network and its design optimization in a petrochemical complex. As demonstrated in the scenarios evaluated, the whole utility network design highly influences the operational costs of the industrial complex. However, the framework presented in this study is a general layout for risk assessment through the risk cost estimation. Therefore, a more specific study, including the addition of risk performance for each facility operation and their detailed operation month-wise, should be developed for future research.

ACKNOWLEDGEMENT

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NOTATION

Abbreviations

EIP : eco-industrial park
 HP : high pressure
 MP : medium pressure
 LP : low pressure
 VHP : very high pressure
 MILP : mixed-integer linear programming
 GAMS : general algebraic modeling system

Sets (Utility)

tnk : fuel tank
 spl : splitter
 mix : mixer
 boil : boiler
 tur : turbine
 sh : steam header
 lu : letdown unit
 wu : water unit
 i : company
 proc : process
 s : demand scenario
 p(s) : inverse of the sum of demand scenarios
 pl : pipeline
 st : state of the material (in: input; gen: generation; out: output; con: consumption)
 fuel : fuel

water : water
 steam : steam
 elec : electricity
 iw : industrial water

Parameters (Utility)

$D_{t,i}^{mat}$: demand of materials (ton/year)
 $Dist_{i,i'}$: distance between source and sink companies [ton/year]
 CP^{invest} : investment cost parameter
 Pri^{fuel} : price of fuel [ton/year]
 Pri^{water} : price of water [ton/year]
 FC^{invest} : fixed investment cost parameter [\$/ton]
 FC^{oper} : fixed operating parameter [\$/ton]
 VC^{cap} : variable investment cost parameter (cap: invest or operation) [\$/ton]

Variables (Utility)

$bi_{s,i,boil,steam}^{steam}$: binary variable of steam amount (boiler)
 $bi_{i,e,HS,IN}^{tur}$: binary variable of steam amount (turbine)
 $bi_{i,b,m,IN}^{spl}$: binary variable of steam amount (splitter)
 $bi_{i,c,m,IN}^{mix}$: binary variable of steam amount (mixer)
 $bi_{i,i',sh}^{steam}$: binary variable of steam transfer
 $bi_{s,i,i',sh}^{tr}$: binary variable of steam transfer (tr: tr1, tr2)
 $bi_{s,i,i',sh}^{tr}$: binary variable of steam transfer (tr: tr1, tr2) (second stage)
 $br_{s,i,boil,steam}^{oper}$: binary variable of boiler operation
 $br_{s,i,tur,steam}^{oper}$: binary variable of turbine operation
 $br_{s,i,spl,fuel}^{oper}$: binary variable of splitter operation
 $br_{s,i,mix,fuel}^{oper}$: binary variable of mixer operation
 $Cost_{s,i,i',sh,steam}^{invest}$: total investment cost [\$/year]
 $Cost_{s,i,i',sh,steam}^{oper}$: total operating cost [\$/year]
 $Cost_{s,i,i',sh,steam}^{oper}$: total operation cost [\$/year] (second stage)
 $Cost_{s,i}^{Raw}$: total raw material cost [\$/year]
 $E_{s,i,fac,st}^{mat}$: materials exchange between facilities (mat: fuel, steam, water; fac: tnk, spl, mix, tur, wu, lu, proc) [\$/year]
 $A_{s,i,fac,st}^{mat}$: amount of materials transferred (mat: fuel, steam, water; fac: tnk, spl, mix, tur, wu, lu, proc) [ton/year]
 $A_{s,i,boil,con}^{fuel}$: fuel amount (con: consumption) [ton/year]
 $A_{s,i,wu,con}^{water}$: water amount (con: consumption) [ton/year]
 $A_{s,i,elec,con}^{elec}$: electricity amount (con: consumption) [ton/year]
 $Total_{Cost,first\ stage}^{Economic}$: total economic cost in the first stage [ton/year]
 $Total_{Cost,second\ stage}^{Economic}$: total economic cost in the second stage [ton/year]

Risk Variables

C^{pl} : installation cost of pipelines [\$/km]
 C^{boil} : installation cost of boiler [\$/unit]
 C^{tur} : installation cost of turbine [\$/unit]
 C^{spl} : installation cost of splitter [\$/unit]
 C^{mix} : installation cost of mixer [\$/unit]
 $fail^{pl}$: failure rate of pipelines [failure /km]
 $fail^{boil}$: failure rate of boiler [failure /h]
 $fail^{tur}$: failure rate of turbine [failure /h]
 $fail^{spl}$: failure rate of splitter [failure /h]
 $fail^{mix}$: failure rate of mixer [failure /h]
 $Risk_{i,i'}^{pl}$: failure risk of pipelines (failure probability)
 $Risk_{s,i}^{boil}$: failure risk of boiler (failure probability)

SUPPORTING INFORMATION

Additional information as noted in the text. This information is available via the Internet at <http://www.springer.com/chemistry/journal/11814>.

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Supporting Information

Optimal utility supply network under demand uncertainty for operational risk assessment on a petrochemical industrial park

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Study Area

This paper considers the Yeosu industrial park (YIP) of South Korea as scenario. YIP was created by the Korea Water Resources Corporation and Korea Industrial Complex Corporation, and in 2013 it was converted into an eco-industrial park (EIP). The industrial park is strategically located in the proximity of Jungheung-dong and Samil-dong, Yeosu city, South Korea; taking advantage of the favorable conditions of a seaside site [1]. The pipeline network for steam transfer was designed during construction of the industrial park. However, over the years, the industrial production has varied, while the steam transfer has not been optimized to these conditions. The steam amount generated by companies in the Yeosu utility network has been previously measured for companies like Hansol EME, who recorded the production of medium-pressure (MP) steam of 10 kgf/cm², and the KP Chemical company, who supplied high pressure (HP) steam of 45 kgf/cm² [1]. Overall, the minimum steam production amount in 2010 was defined as 3,075 ton/h of very high-pressure (VHP) steam, 514 ton/h of HP steam, and 153 ton/h of MP steam, while the maximum steam production was 3,717 ton/h of VHP steam, 1,172 ton/h of HP steam, and 248 ton/h of MP steam [1]. Thus, the utility supply network has reported profits of 68.52 million dollars per year, while the investment cost was 64.93 million dollars [1].

Problem Statement

Varied cases of failure rate were used in the assumption of an average failure rate for possible interruption of the operation of the facilities in the utility supply network. For a boiler unit, there were

considered the superheater, water-wall tubes, air preheater, and fan as principal mechanisms of failure in the boiler. For the turbine, the steam transfer characteristics from previous studies were used, and base records from previous studies were used for the mixer and splitter [2-6].

Mass Balance of the Utility Supply Network

A material balance method was used for defining the constraints of the system and to represent the utility supply network. This method assumes the operability of the network at a steady state, which means that there is no loss of materials in the transfer between facilities and companies. Eqs. (1) and (2) represent the material balance equations for the whole utility supply network. Here, $D_{s,i}^{mat}$ is the demand for materials in the network, $A_{s,i, fac, st}^{mat}$ is the amount of materials transferred by facilities, and $E_{s,i, fac, st}^{mat}$ is the materials exchange by facilities. The materials are the fuel, water, and electricity transferred between facilities. The different demand scenarios are represented as s , by each company i . The facilities (fac) are defined as the fuel tank, splitter, mixer, boiler, turbine, let-down unit, water unit process, and pipeline. The state (st) refers to the input or output of the material from the facility where it is being consumed or generated. A more detailed description of each variable is presented in the nomenclature. Eq. (S1) represents the amount of material in the facilities of any company that should meet their demand under the demand scenario condition. Eq. (S2) shows the total amount of exchanged material in the facilities, which should not exceed the original amount of material in the facilities. More details related to the mass balance for each facil-

Table S1. Description of scenarios for the optimization problem

No.	Scenario	Description
1	Base case	Base utility network by deterministic approach.
2	Optimized base case	Economic cost optimization by deterministic approach.
3	Stochastic optimized case	Economic cost optimization by stochastic approach (demand uncertainty).
4	Two-objective two-stage stochastic optimized case with integrated operation risk of pipelines	Economic cost and pipeline risk cost optimization by stochastic approach (demand uncertainty).
5	Two-objective two-stage stochastic case with integrated operation risks for all facilities	Economic cost and risk cost optimization for the whole utility supply network by a stochastic approach (demand uncertainty).

Table S2. SO_x and GHG emission parameter according to the fuel type. Adapted from [7]

Fuel type	SO _x emission parameter (pri _q)	GHG emission (emission _m ^{GHG}) [ton/ton fuel]
f1	0.022	0.017
f2	0.004	0.005
f3	0.003	0.003
f4	0.003	0.003

ity are presented in Supplementary information, and a deeper understanding can be found in the previous studies of [7] and [8].

$$D_{s,i}^{mat} \leq A_{s,i, fac, st}^{mat} \quad (S1)$$

$$A_{s,i, fac, st}^{mat} = \sum_{fac} E_{s,i, fac, st}^{mat} \quad (S2)$$

Common Constraints

The steam injected at each company should be greater than the steam demand for their process (Eq. (S3)):

$$Dist_{t, ip} \leq x_{t, i, k, p, "IN"} \quad (S3)$$

As shown in Eq. (S4), the steam injected is transferred from the steam header to the process. The binary values of the steam amount and steam transfer are presented in Eqs. (S5) to (S9). Eq. (S5) is adapted for the turbines (Eq. (S6)), splitters (Eq. (S7)), and mixers (Eq. (S8)) of each company.

$$x_{t, i, k, p, "IN"} = \sum_f e_{t, i, f, k, p} \quad (S4)$$

$$\frac{b_{t, i, d, p, l}}{BM} \leq x_{t, i, d, p, l} \leq (b_{t, i, d, p, l})(BM) \quad (S5)$$

$$\frac{b_{t, i, e, "HS", "IN"}^{turbine}}{BM} \leq x_{t, i, e, "HS", "IN"} \leq (b_{t, i, e, "HS", "IN"}^{turbine})(BM) \quad (S6)$$

$$\frac{b_{t, i, b, m, "IN"}^{splitter}}{BM} \leq x_{t, i, b, m, "IN"} \leq (b_{t, i, b, m, "IN"}^{splitter})(BM) \quad (S7)$$

Table S3. Maximum steam production capacity. Adapted from [7]

Company	Boiler type	Steam type	Maximum capacity (steam _{t, i, d, p} ^{max}) [ton/year]
6	b1	VHS	1270200
	b2	HS	525600
7	b2	HS	1379700
8	b4	LS	109500
9	b3	MS	1051200
10	b1	VHS	1971000
	b2	HS	1971000
11	b1	VHS	1971000
	b2	HS	1379700
12	b3	MS	919800
	b4	LS	876000
13	b2	HS	197100
14	b1	VHS	1379700
	b2	HS	2190000
15	b1	VHS	1839600
	b2	HS	240900

$$\frac{b_{t, i, c, m, "IN"}^{mixer}}{BM} \leq x_{t, i, c, m, "IN"} \leq (b_{t, i, c, m, "IN"}^{mixer})(BM) \quad (S8)$$

$$\frac{b_{t, i, ip, f}}{BM} \leq x_{t, i, ip, f} \leq (b_{t, i, ip, f})(BM) \quad (S9)$$

where BM is a large positive value for big-M method of mixed-integer linear programming (MILP) formulation. The Big-M method is an extension of the Simplex algorithm that solves problems containing "greater-than" constraints. The BM value selected in this study, was needed to be sufficiently large for the artificial variable not to be part of a feasible solution [9].

Table S4. Utility, environmental, and equipment cost data

Type	Component	Abbreviation	Cost	Unit	Reference
Utility	Electric power import	Pri(o)	0.06	\$/kWh	[6]
	Electric power export		0.06	\$/kWh	[11]
	f1	Pri(m)	569.09	\$/ton	[11]
	f2		32		[12]
	f3		50.91		[12]
	f4		172.73		[6]
Environmental impact cost	Raw water	Pri(n)	0.05	\$/ton	[6]
	SO ₂	Pri(q)	400	\$/ton	[11]
	CO ₂	Pri(r)	40		[11]
Equipment	Mixer	c	23050	\$	[13]
	Splitter	b	23050	\$	[13]
	Gas turbine	e	650	\$/kWh	[14]
	Boiler	d	2562000	\$	[15]

Table S5. Steam conversion parameter. Adapted from [7]

Steam type 1	Steam type 2	Steam conversion ($Stc_{p,pp}$)
VHS	HS	0.1
VHS	MS	0.18
VHS	LS	0.24
HS	MS	0.07
HS	LS	0.13
MS	LS	0.05

Table S6. Turbine parameters. Adapted from [7]

Utility type	Abbreviation	Turbine parameter
Water (Wt)	Tur(n)	0.001
	HS	0.15
Steam	MS	0.07
	LS	0.009

Table S7. Electricity consumption constants. Adapted from [7]

Boiler type	Fixed ($\alpha_d^{Electricity}$)	Variable ($\beta_d^{Electricity}$)
b1	0.001	0.002
b2	0.001	0.003
b3	0.001	0.0025
b4	0.001	0.0025

Fuel Tank Constraints

The fuel transfers from the fuel tanks to the splitters or boilers. The fuel tank model follows Eqs. (S10) to (S15). Eqs. (S10) and (S11) show the output from the fuel tank to the splitter; if the company does not possess a splitter, the fuel is transferred to the boiler (Eqs. (S12) and (S13)).

$$\sum_a x_{t,i,a,m,"OUT"} = \sum_b x_{t,i,b,m,"IN"} \quad (S10)$$

$$x_{t,i,a,m,"OUT"} = \sum_b e_{t,i,a,b,m} \quad (S11)$$

$$\sum_a x_{t,i,a,m,"OUT"} = \sum_d x_{t,i,d,m,"IN"} \quad (S12)$$

$$x_{t,i,a,m,"OUT"} = \sum_d e_{t,i,a,d,m} \quad (S13)$$

Further, the remaining inventory of fuel is represented by Eq.

(S14), where it is equal to the initial inventory minus the output from the fuel tank. The same remaining inventory must be limited to be less than the minimum inventory value (safety level of the tank) (Eq. (S15)).

$$\text{inventory}_{t,i,a,m}^{\text{remain}} = \text{inventory}_{t,i,a,m}^{\text{initial}} - x_{t,i,a,m,"OUT"} \quad (S14)$$

$$\text{inventory}_{t,i,a,m}^{\text{remain}} \geq (\text{inventory}_{\text{min}}^{\text{ratio}})(\text{inventory}_{t,i,a,m}^{\text{initial}}) \quad (S15)$$

Splitter and Mixer Constraints

The role of the splitter and mixer units is to transfer the materials from the company, from one unit to another. Eqs. (S16) and (S17) show that the output amount from the splitter is equal to the total of the input amount of the mixers.

$$\sum_b x_{t,i,b,m,"OUT"} = \sum_c x_{t,i,c,m,"IN"} \quad (S16)$$

$$x_{t,i,b,m,"OUT"} = \sum_c e_{t,i,b,c,m} \quad (S17)$$

Eq. (S18) presents the fuel transfer for the fuel tank and the splitter, which is the same as the transfer of the splitter and mixer.

$$\sum_a e_{t,i,a,b,m} = \sum_c e_{t,i,b,c,m} \quad (S18)$$

Eq. (S19) similarly portrays the balance equation in which the fuel exchange is maintained from the transfer between the splitter and mixer, and between the mixer and boiler.

$$\sum_b e_{t,i,b,c,m} = \sum_d e_{t,i,c,d,m} \quad (S19)$$

Hence, the output from the mixer is equal to the input of the boiler (Eqs. (S20) and (S21)).

$$\sum_b x_{t,i,c,m,"OUT"} = \sum_d x_{t,i,d,m,"IN"} \quad (S20)$$

$$x_{t,i,c,m,"OUT"} = \sum_d e_{t,i,c,d,m} \quad (S21)$$

Boiler Constraints

The output from the boilers includes the steam, SO_x and GHGs. Steam is a principal energy source classified into four types based on their pressure and temperature. Table S2 presents details of the steam properties for each type of steam, such as very high-pressure steam (VHS), high-pressure steam (HS), medium-pressure steam (MS), and low-pressure steam (LS). The boiler model is presented in the following equations (Eqs. (S22) to (S30)). The steam gener-

Table S8. Failure rate of main components of the utility network of the Yeosu industrial complex

Equipment	Description	Average failure rate	Unit	Reference
Pipe	Diameter larger than 3 in	3×10^{-7}	/km	[2]
Boiler	N/A	8.6×10^{-6}	/h	[4]
Splitter	N/A	6.54×10^{-8}	/h	[5]
Turbine	N/A	7.197×10^{-5}	/h	[3]
Mixer	N/A	7.947×10^{-7}	/h	

N/A: Not available

ated must be less than the maximum capacity of the boiler (Eq. (S22)). The boiler is considered to have a minimum steam generation capacity as well (Eq. (S23)).

$$x_{t,i,d,p,"GEN"} \leq \text{steam}_{t,i,d,p}^{\max} \quad (\text{S22})$$

$$(\text{steam}_{t,i,d,p}^{\min})(b_{t,i,d,p,"GEN"}) \leq x_{t,i,d,p,"GEN"} \quad (\text{S23})$$

Table S9. Utility demand by company. Adapted from [7]

Period	Company	Steam ($D_{t,i,p}$) [ton/year]				Water ($D_{t,i,n}$) [ton/year]	Electricity ($D_{t,i}^{\text{electricity}}$) [kWh/year]
		VHS	HS	MS	LS		
t ₁	1	0	0	70000	0	0	99000
	2	0	0	183000	278000	119000	199000
	3	0	0	119000	99000	119000	159000
	4	0	0	28000	40000	0	99000
	5	0	0	0	12000	0	40000
	6	0	0	0	0	0	0
	7	0	0	0	50000	99000	99000
	8	0	129000	91000	14000	238000	199000
	9	0	0	334000	191000	99000	139000
	10	894000	894000	0	0	497000	238000
	11	894000	1081000	342000	229000	437000	238000
	12	0	0	62000	364000	119000	99000
	13	0	229000	68000	28000	199000	139000
	14	1212000	445000	419000	227000	497000	397000
	15	837000	147000	131000	141000	397000	338000
t ₂	1	0	0	60000	0	0	99000
	2	0	0	99000	159000	119000	199000
	3	0	0	119000	99000	119000	159000
	4	0	0	28000	40000	0	99000
	5	0	0	0	12000	0	40000
	6	0	0	0	0	0	0
	7	0	0	0	50000	99000	99000
	8	0	99000	70000	0	238000	199000
	9	0	0	219000	139000	99000	139000
	10	874000	596000	0	0	497000	238000
	11	854000	795000	342000	229000	437000	238000
	12	0	0	40000	238000	119000	99000
	13	0	229000	60000	28000	199000	139000
	14	1192000	417000	419000	219000	497000	397000
	15	837000	139000	131000	129000	397000	338000
t ₃	1	0	0	50000	0	0	99000
	2	0	0	40000	79000	119000	159000
	3	0	0	109000	89000	119000	159000
	4	0	0	20000	36000	0	99000
	5	0	0	0	10000	0	40000
	6	0	0	0	0	0	0
	7	0	0	0	40000	99000	99000
	8	0	52000	46000	0	159000	199000
	9	0	0	133000	0	0	139000
	10	860000	318000	0	0	457000	238000
	11	825000	686000	342000	229000	358000	238000
	12	0	0	20000	109000	119000	99000
	13	0	219000	50000	28000	199000	139000
	14	1164000	413000	417000	191000	497000	358000
	15	823000	125000	131000	119000	397000	298000

Table S9. Continued

Period	Company	Steam ($D_{t,i,p}$) [ton/year]				Water ($D_{t,i,n}$) [ton/year]	Electricity ($D_{t,i}^{electricity}$) [kWh/year]
		VHS	HS	MS	LS		
	1	0	0	56000	0	0	99000
	2	0	0	99000	159000	119000	159000
	3	0	0	119000	99000	119000	159000
	4	0	0	24000	40000	0	99000
	5	0	0	0	12000	0	40000
	6	0	0	0	0	0	0
	7	0	0	0	50000	99000	99000
t_4	8	0	79000	70000	0	159000	199000
	9	0	0	219000	139000	0	139000
	10	874000	397000	0	0	457000	238000
	11	854000	795000	342000	229000	358000	238000
	12	0	0	40000	238000	119000	99000
	13	0	229000	60000	28000	199000	139000
	14	1172000	417000	419000	219000	497000	358000
	15	831000	139000	131000	129000	397000	298000

Further, Eq. (S24) portrays the steam generation as a function of the calorific value, fuel consumed by the boiler, and the boiler efficiency. The output amount of steam is equal to the sum of all the steam header input amounts as presented by Eq. (S25).

$$x_{t,i,d,p,"GEN"} = \sum_m \left(\frac{\text{caloric}_m(x_{t,i,d,m,"CON"})}{\text{efficiency}_{d,m}} \right) \quad (S24)$$

$$x_{t,i,d,p,"OUT"} = \sum_f e_{t,i,d,f,p} \quad (S25)$$

Eq. (S26) presents the generation of steam that occurs in the company, which commonly happens alongside the generation of waste load due to the water and fuel consumption. Eq. (S27) presents the limit for water that should be consumed in the boiler.

$$\begin{aligned} \sum_m x_{t,i,d,m,"IN"} + \sum_n x_{t,i,d,n,"IN"} \\ = \sum_p x_{t,i,d,p,"GEN"} + \sum_q x_{t,i,d,q,"GEN"} + \sum_r x_{t,i,d,r,"GEN"} \end{aligned} \quad (S26)$$

$$x_{t,i,d,n,"IN"} = x_{t,i,d,n,"CON"} \quad (S27)$$

The electricity consumption is presented based on the steam generated (Eq. (S28)). Similarly, the SO_x and GHG generated are proportional to the fuel consumed by the boiler (Eqs. (S29) and (S30)).

$$Y_{t,i,"CON"} = \sum_p \left((\alpha_d^{electricity})(b_{t,i,d,p,"GEN"}) + (\beta_d^{electricity})(x_{t,i,d,p,"GEN"}) \right) \quad (S28)$$

$$\sum_q x_{t,i,d,q,"GEN"} = \sum_m (\text{emission}_m^{SO_x})(x_{t,i,d,m,"CON"}) \quad (S29)$$

$$\sum_r x_{t,i,d,r,"GEN"} = \sum_m (\text{emission}_m^{GHG})(x_{t,i,d,m,"CON"}) \quad (S30)$$

Turbine Constraints

The amount of electricity generated is based on the WT and steam input as HS, MS, LS of the turbine unit, for which the HS input amount is the sum of the rest of the types of steam and water generation (Eqs. (S31) and (S32)).

$$Y_{t,i,"GEN"} = \sum_e \left((\text{turbine}_{"HS"}^{steam})(x_{t,i,e,"HS","IN"}) - (\text{turbine}_{"MS"}^{steam})(x_{t,i,e,"MS","GEN"}) - (\text{turbine}_{"LS"}^{steam})(x_{t,i,e,"LS","GEN"}) - (\text{turbine}_{"WT"}^{steam})(x_{t,i,e,"WT","GEN"}) \right) \quad (S31)$$

$$x_{t,i,e,"HS","IN"} = x_{t,i,e,"MS","GEN"} + x_{t,i,e,"LS","GEN"} + x_{t,i,e,"WT","GEN"} \quad (S32)$$

The generated MS/LS is transferred from the turbine to the MSH/LSH (Eqs. (S33) and (S34)). The HS input amount is the steam transferred from the header to the turbine unit (Eq. (S35)).

$$x_{t,i,e,"MS","OUT"} = e_{t,i,e,"MSH","MS"} \quad (S33)$$

$$x_{t,i,e,"LS","OUT"} = e_{t,i,e,"LSH","LS"} \quad (S34)$$

$$x_{t,i,e,"HS","IN"} = \sum_f e_{t,i,f,e,"HS"} \quad (S35)$$

Eq. (S36) presents the generation of the condensate, which is proportional to the HS input amount of the turbine.

$$x_{t,i,e,"wt","GEN"} = (\text{ConP})(x_{t,i,e,"hs","IN"}) \quad (S36)$$

Steam Header Constraints

Eqs. (S37) and (S38) refer to the input and output of a steam header. These parameters are related to the transfer between companies, steam exchange with the other facilities, as well as process and steam vents.

$$x_{t,i,f,p,"IN"} = \sum_{ip} r_{t,i',i,f} + \sum_d e_{t,i,d,f,p} + \sum_e e_{t,i,e,f,p} + \sum_g e_{t,i,g,f,p} \quad (S37)$$

$$x_{t,i,f,p,"OUT"} = \sum_{ip} r_{t,i,i',f} + \sum_e e_{t,i,f,e,p} + \sum_g e_{t,i,f,g,p} + \sum_k e_{t,i,f,k,p} \quad (S38)$$

Scenarios

The proposed two-objective two-stage stochastic model was developed in the software GAMS (General Algebraic Modeling System) v24.6, which utilizes the CPLEX solver [10]. There were conducted five scenarios for operational risk assessment (Table S1). The base case outlines the utility supply network optimization based

Table S10. Distance between source and sink companies (Dist_{i, ip}). Adapted from [7]

Company	1 ^a	6	2 ^a	3 ^a	4 ^a	7	8	5 ^a	9	10	11	12	13	14	15
1		500	825	1020	2886	141	2663	200	1844	2506	3421	906	3231	2000	2110
6	500		412	608	2518	539	2163	412	1345	2062	3041	640	2816	1526	1703
2	825	412		200	2602	906	1910	800	1166	2040	3102	316	2828	1456	1300
3	1020	608	200		2617	1105	1769	1000	1077	2010	3102	316	2807	1414	1100
4	2886	2518	2602	2617		2816	1985	2693	1746	781	539	2907	539	1300	2953
7	141	539	906	1105	2816		2693	141	1860	2470	3353	1020	3178	1985	2202
8	2663	2163	1910	1769	1985	2693		2555	854	1221	2220	2062	1803	1005	1304
5	200	412	800	1000	2693	141	2555		1720	2332	3228	949	3046	1844	2100
9	1844	1345	1166	1077	1746	1860	854	1720		1020	2159	1393	1811	447	1221
10	2506	2062	2040	2010	781	2470	1221	2332	1020		1140	2319	800	600	2193
11	3421	3041	3102	3102	539	3353	2220	3228	2159	1140		3400	424	1726	3324
12	906	640	316	316	2907	1020	2062	949	1393	2319	3400		3114	1726	1237
13	3231	2816	2828	2807	539	3178	1803	3046	1811	800	424	3114		1400	2941
14	2000	1526	1456	1414	1300	1985	1005	1844	447	600	1726	1726	1400		1664
15	2110	1703	1300	1100	2953	2202	1304	2100	1221	2193	3324	1237	2941	1664	

^aSink company

on a multi-period deterministic model from previous research by [7]. Scenario 2 illustrates the optimized utility supply network with updated materials cost values for inversion costs in the present conditions. Scenario 3 evaluates the economic cost integrated with the utilities demand uncertainty. Scenario 4 analyses the economic cost and risk cost of pipelines in the optimization model. Scenario 5 presents a full two-stage stochastic model that evaluates the economic cost and risk cost of the utility supply network and its facilities for all the companies.

Scenarios 1 and 2

Scenario 1 is the base case, which utilizes a multi-period deterministic model based on the previous research proposed by [7].

Table S11. Calorific values and boiler efficiencies by fuel type. Adapted from [7]

Boiler type	Fuel type	Calorific value (calorific _m)	Boiler efficiency (efficiency _{a,m})
b ₁	f ₁	15.19	0.59
	f ₂	12.67	0.59
	f ₃	9.79	0.59
	f ₄	9.79	0.59
b ₂	f ₁	15.19	0.58
	f ₂	12.67	0.58
	f ₃	9.79	0.57
	f ₄	9.79	0.57
b ₃	f ₁	15.19	0.56
	f ₂	12.67	0.56
	f ₃	9.79	0.56
	f ₄	9.79	0.56
b ₄	f ₁	15.19	0.56
	f ₂	12.67	0.56
	f ₃	9.79	0.56
	f ₄	9.79	0.55

The steam delivery by seasons of the year was primarily considered in this design. The optimized utility supply network integrated the previous conditions of the industrial complex, considering past cost values for each material tracked in the utility supply network.

Table S12. General constant parameters. Adapted from [7]

Constant parameter	Values
Condensate parameter (ConP)	0.25
Minimum distance (Dist ^{min}) [km]	1
Depreciation parameter (DP)	7
Minimum inventory ratio (inventory ^{ratio} _{min})	0.2
Investment cost parameter (IP)	2
Pressure drop cost parameter (PP) [\$/year×km]	1
Repairment cost parameter (RP) [\$/year×km]	0.1

Table S13. Configuration of companies. Adapted from [7]

Company	Fuel tank	Splitter	Mixer	Boiler	Turbine
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	-	-	-	-	-
6	2	2	2	2	1
7	1	-	-	1	-
8	1	-	-	1	-
9	1	-	-	1	1
10	2	2	2	2	1
11	2	2	2	2	1
12	2	-	-	2	-
13	1	-	-	1	-
14	2	2	2	2	1
15	2	2	2	2	1

Table S14. Fuel consumption in companies. Adapted from [7]

Company	Fuel type input at splitter	Fuel type input at mixer
2	f_1	f_1
2	f_4	f_4
6	f_3	f_3
7	f_4	f_4
9	f_2	f_2
10	f_2	f_2
10	f_3	f_3
11	f_1	f_1
11	f_4	f_4
12	f_3	f_3
12	f_4	f_4
13	f_2	f_2
14	f_1	f_1
14	f_4	f_4
15	f_1	f_1
15	f_2	f_2

Table S15. Initial inventory of the fuel tank. Adapted from [7]

Company	Fuel tank type	Fuel type	Inventory [ton]
2	ft_1	f_1	120
	ft_4	f_4	130
6	ft_3	f_3	130
7	ft_4	f_4	120
9	ft_2	f_2	130
10	ft_2	f_2	130
	ft_3	f_3	120
11	ft_1	f_1	120
	ft_4	f_4	130
12	ft_3	f_3	120
	ft_4	f_4	130
13	ft_2	f_2	120
14	ft_1	f_1	120
	ft_4	f_4	130
15	ft_1	f_1	120
	ft_2	f_2	130

Table S16. Steam properties. Adapted from [7]

Property	VHS	HS	MS	LS	Unit
Temperature	525	370	270	195	°C
Pressure	121.5	40.0	15.0	3.5	atm
Enthalpy	3422	3156	2982	2858	kJ/kg

The estimated economic cost for this case was 276 million dollars. Furthermore, scenario 2 was similarly developed as a deterministic model with seasonal variation. However, an update of the cost values of materials (electricity, fuel, and equipment) for a correct estimation of the economic cost was considered. The updated val-

ues are presented in Table S3, and the economic cost of scenario 2 was estimated around 89 million dollars.

Utility Supply Network Configuration

This section presents illustration and tables referred to the configuration of the utility network, the companies, their facilities, the steam transfer conditions, and the utilities conditions in general.

NOTATION

Abbreviations

YIP : yeosu industrial park
 EIP : eco-industrial park
 HP : high pressure
 MP : medium pressure
 VHP : very high pressure
 MILP : mixed-integer linear programming
 GAMS : general algebraic modeling system

Sets (Utility)

a : fuel tank
 b : splitter
 c : mixer
 d : boiler
 e : turbine
 f : steam header
 g : letdown unit
 h : water unit
 i : company
 ip : sink company
 k : process
 l : state of the material (IN: input; GEN: generation; OUT: output; CON: consumption)
 m : fuel
 n : water
 p : steam
 q : SO_x
 r : greenhouse gas (GHG)
 t : period (demand by time)

Parameters (Utility)

$\alpha_d^{electricity}$: fixed electricity consumption constant (boiler)
 $\alpha_{t,i,ip,f}^{invest}$: fixed investment cost parameter [\$/year-km]
 $\alpha_{t,i,ip,f}^{operation}$: fixed operation cost parameter [\$/year-km]
 $\beta_d^{electricity}$: variant electricity consumption constant (boiler)
 $\beta_{t,i,ip,f}^{invest}$: variant investment cost parameter [\$/km-ton]
 $\beta_{t,i,ip,f}^{operation}$: variant operation cost parameter [\$/km-ton]
 calorific_m : calorific value
 ConP : condensate parameter
 $D_{t,i,n}$: water demand [ton/year]
 $D_{t,i,p}$: steam demand [ton/year]
 $D_{t,i}^{electricity}$: electricity demand [kwh/year]
 $Dist_{t,ip}$: distance between source and sink companies [km]
 $Dist^{min}$: minimum distance [km]
 DP : depreciation parameter
 efficiency_{d,m} : boiler efficiency
 emission_m^{GHG} : GHG emission parameter [ton/ton_{fuel}]

$\text{emission}_m^{SO_x}$: SO_x emission parameter [ton/ton_{fuel}]
 $\text{inventory}_{min}^{ratio}$: minimum inventory ratio
 $\text{inventory}_{i,a,m}^{initial}$: initial inventory [ton]
 IP : investment cost parameter
 PP : pressure drop cost parameter [\$/year·km]
 pri_m : fuel price [\$/ton]
 pri_n : water price [\$/ton]
 pri_q : SO_x emission parameter [ton/ton_{fuel}]
 pri_r : GHG cleanup cost [\$/ton]
 $\text{pri}^{electricity}$: electricity price [\$/kwh]
 RP : repairment cost parameter [\$/year·km]
 $\text{Stc}_{p,pp}$: steam converting parameter
 $\text{steam}_{i,d,p}^{max}$; maximum steam production [ton/year]
 $\text{steam}_{i,d,p}^{min}$: minimum steam production [ton/year]
 turbine_n^{water} : turbine water parameter
 turbine_p^{steam} : turbine steam parameter

Variables (Utility)

$b_{t,i,d,p,l}$: binary variable of steam amount (boiler)
 $b_{t,i,e}^{turbine}$, "HS", "IN" : binary variable of steam amount (turbine)
 $b_{t,i,b,m}^{splitter}$, "IN" : binary variable of steam amount (splitter)
 $b_{t,i,c,m}^{mixer}$, "IN" : binary variable of steam amount (mixer)
 $br_{t,i,ip,f}$: binary variable of steam transfer
 $br1_{t,i,ip,f}$: binary variable of steam transfer 1
 $br2_{t,i,ip,f}$: binary variable of steam transfer 2
 C_t^{risk} : total risk cost [\$/year]
 $C_{t,i,ip,f}^{invest}$: total investment cost [\$/year]
 $C_{t,i,ip,f}^{operation}$: total operation cost [\$/year]
 $C_{t,i}^{raw}$: total raw material cost [\$/year]
 C^{pipe} : installation cost of pipe [\$/km]
 C^{boiler} : installation cost of boiler [\$/unit]
 $C^{turbine}$: installation cost of turbine [\$/unit]
 $C^{splitter}$: installation cost of splitter [\$/unit]
 C^{mixer} : installation cost of mixer [\$/unit]
 $e_{t,i,a,b,m}$: fuel exchange between fuel tank and splitter [ton/year]
 $e_{t,i,a,d,m}$: fuel exchange between fuel tank and boiler [ton/year]
 $e_{t,i,b,c,m}$: fuel exchange between splitter and mixer [ton/year]
 $e_{t,i,c,d,m}$: fuel exchange between mixer and boiler [ton/year]
 $e_{t,i,d,f,p}$: steam exchange between boiler and steam header [ton/year]
 $e_{t,i,e,f,p}$: steam exchange between turbine and steam header [ton/year]
 $e_{t,i,e,h,n}$: water exchange between turbine and water unit [ton/year]
 $e_{t,i,f,e,p}$: steam exchange steam header and turbine [ton/year]
 $e_{t,i,f,g,p}$: steam exchange steam header and letdown unit [ton/year]
 $e_{t,i,f,k,p}$: steam exchange steam header and process [ton/year]
 $e_{t,i,g,f,p}$: steam exchange between letdown unit and steam header [ton/year]
 $e_{t,i,h,d,n}$: water exchange between water unit and boiler [ton/year]
 $e_{t,i,h,g,n}$: water exchange between water unit and letdown unit [ton/year]
 $e_{t,i,h,k,n}$: water exchange between water unit and process [ton/year]
 fail^{pipe} : failure rate of pipe [failure /km]
 fail^{boiler} : failure rate of boiler [failure /h]
 $\text{fail}^{turbine}$: failure rate of turbine [failure /h]
 $\text{fail}^{splitter}$: failure rate of splitter [failure /h]

fail^{mixer} : failure rate of mixer [failure /h]
 $\text{inventory}_{t,i,a,m}^{remain}$: remaining inventory [ton]
 $r_{t,i,ip,f}$: steam transfer [ton/year]
 $r1_{t,i,ip,f}$: steam transfer 1 [ton/year]
 $r2_{t,i,ip,f}$: steam transfer 2 [ton/year]
 $\text{Risk}_{i,ip,f,p}^{pipeline}$: risk of failure of pipeline (failure probability)
 $\text{Risk}_{t,i,d,p}^{boiler}$, "OUT" : risk of failure of boiler (failure probability)
 $\text{Risk}_{t,i,e}^{turbine}$, "HS", "IN" : risk of failure of turbine (failure probability)
 $\text{Risk}_{t,i,b,m}^{splitter}$: risk of failure of splitter (failure probability)
 $\text{Risk}_{t,i,c,m}^{mixer}$, "IN" : risk of failure of mixer (failure probability)
 $v_{t,i,f}$: vented steam [ton/year]
 $x_{t,i,a,m,l}$: fuel amount at fuel tank [ton/year]
 $x_{t,i,b,m,l}$: fuel amount at splitter [ton/year]
 $x_{t,i,c,m,l}$: fuel amount at mixer [ton/year]
 $x_{t,i,d,m,l}$: fuel amount at boiler [ton/year]
 $x_{t,i,e,n,l}$: water amount at turbine [ton/year]
 $x_{t,i,e,p,l}$: steam amount at turbine [ton/year]
 $x_{t,i,d,n,l}$: water amount at boiler [ton/year]
 $x_{t,i,d,p,l}$: steam amount at boiler [ton/year]
 $x_{t,i,d,q,l}$: SO_x amount at boiler [ton/year]
 $x_{t,i,d,r,l}$: GHG amount at boiler [ton/year]
 $x_{t,i,f,p,l}$: steam amount at steam header [ton/year]
 $x_{t,i,g,n,l}$: water amount at letdown unit [ton/year]
 $x_{t,i,g,p,l}$: steam amount at letdown unit [ton/year]
 $x_{t,i,h,n,l}$: water amount at water unit [ton/year]
 $x_{t,i,k,n,l}$: water amount in the process [ton/year]
 $x_{t,i,k,p,l}$: steam amount in the process [ton/year]
 $Y_{t,i,l}$: electricity amount [kwh/year]
 Z : total cost [\$/year]

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