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APPLICATIONS OF A FUZZY GOAL PROGRAMMING TO QUALITY CONTROL SYSTEM DESIGN

تطبيقات البرمجة بالأهداف الضبابية في تصميم نظام مراقبة الجودة

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Received on: 2026-04-19

Accepted on: 2026-04-28

published on: 2026-06-11

Abstract:

Fuzzy Goal Programming (FGP) has been widely applied in the design of quality control systems (QCS) within industrial firms. This study aims to present two alternative formulations for developing a QCS based on the FGP framework. The approach to fuzzy goal programming introduced by Hannan (1981) is employed to address the QCS problem. The proposed formulations are demonstrated through a case study in the paper industry, using the same example originally developed by Sengupta (1981).

Keys words: Fuzzy goal programming, Minmax approach, Additive approach, quality control System, Membership functions

JEL classification codes: C61; C44; M11; C63

ملخص: البرمجة بالأهداف المبهمة هي أحد النماذج الرياضية الحديثة والتي تمكن المسيرين في حل مشكلة تصميم نظام للرقابة على الجودة داخل المؤسسات الصناعية، وعليه فإن هدف هذه الورقة البحثية هو حل مشكلة تصميم نظام للرقابة على الجودة عن طريق تقديم نموذجين يعتمدان على الصياغة الرياضية التي قدمها Hannan(1981) في حل نموذج البرمجة بالأهداف المبهمة (FGP)، في الأخير قمنا بتطبيق النموذجين على مشكلة صناعة الورق وهي نفس المشكلة التي قدمها Sengupta(1981).

الكلمات المفتاحية: البرمجة بالأهداف المبهمة، مقارنة Minmax، مقارنة Additive، نظام الرقابة على الجودة، دوال الإنتماء.

تصنيف JEL: C63، M11، C44، C61

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1. Introduction

Nowadays, real-world problems in management and economic sciences typically involve non-deterministic systems characterized by multiple, conflicting, and non-commensurable objectives. In response, there has been a significant evolution in methodologies designed to support the decision-making process, particularly in the area of multi-criteria decision-making. Goal Programming (GP) is among the earliest approaches in management science to

address decision problems involving multiple objectives, and it has proven to be a robust and effective tool for modeling real-world decision situations. Numerous recent applications of GP in management have been explored. In this paper, we introduce this approach and outline its underlying philosophy for designing a quality control system (QCS) in the presence of certain features that make it a complex decision-making problem.

Sengupta (1981) proposed a lexicographic GP model for QCS design in the paper industry, determining the levels of inputs and process variables required to meet specified output standards, which is a common objective in QCS design. Schniederjans and Karuppan (1995) developed a new GP-based formulation for QCS design in service organizations, employing a zero-one GP model to assist in selecting the optimal set of quality control instruments for customer data collection. Badri (2001) extended this model by integrating the Analytic Hierarchy Process (AHP) with GP for designing QCS in service organizations. Lee and Wen (1997) applied fuzzy goal programming (FGP), originally developed by Hannan (1981), to water quality management in a river basin. Sadok et al. (2008) proposed two formulations for QCS design based on an imprecise GP model: the first relying on Hannan's (1981) Minmax approach, and the second based on GP with satisfaction functions later developed by Martel and Aouni (1990). These formulations were applied to the paper industry.

This study presents two formulations for QCS design based on additive FGP, as developed by Hannan (1981). The first formulation maximizes the degree of membership functions, while the second minimizes the additive sum of deviations. The proposed approach is illustrated through an application to the paper industry, using the same example developed by Sengupta (1981).

1- GP Approach for designing to QCS in the paper factory

1-1 Sengupta's approach

Sengupta (1981) examined a process control problem in the paper industry, where the levels of input variables ($X_1; \dots; X_l$) and process variables ($R_1; \dots; R_k$) must be determined in order to satisfy the required specifications of several output characteristics ($Y_1; \dots; Y_r$). The allowable ranges for both input and process variables are predefined. The desired output characteristics are either expressed as acceptable intervals or defined in terms of target values of the "close-to" type. The objective is to identify a solution in which the selected input and process variable levels satisfy all output specifications within their respective constraints; if such a solution cannot be achieved, the goal is to determine the best possible compromise.

The relationships between output quality characteristics, input variables, and process variables are established using multiple linear regression analysis. These relationships are subsequently incorporated into a GP formulation with a preemptive priority structure to address the problem.

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The specific details of the input variables, process variables, and output characteristics in the paper industry are presented in Table 1.

Table 1. Target specification for input characteristic, process variables, and output characteristics

Specification/permissible limit		
Input characteristic	(X_1) Hardwood (%)	[20, 40]
Process variables	(R_1) Upper cooking zone temperature (°C)	[140, 175]
	(R_2) Lower cooking zone temperature (°C)	[140, 173]
	(R_3) LP steam pressure (kg/cm ²)	[2,0, 4,4]
	(R_4) HP steam pressure (kg/cm ²)	[8,0, 20,5]
	(R_5) Active alkali as NaOH (%)	[20, 35]
	(R_6) Sulphidity of white liquor (%)	[13, 25]
	(R_7) Alkali index (no)	[12,5, 18,7]
Output characteristics	(Y_1) K-number (Y_2) Burst factor (Y_3) Breaking length	[16, 18] Close to 35 Close to 5000

Source: Authors' own elaboration.

The problem was to fix the levels of the input and the process variables so that specification is met. A follow-up study was undertaken linking the input with the output through the process variables. 46 sets of such data were collected over a period of 13 days. Multiple linear regression analysis was undertaken and the following relationships were obtained.

$$Y_1 = 22.84 + 0.06X_1 - 0.05R_1 + 0.004R_2 - 0.67R_3 + 0.24R_4 - 0.13R_5 + 0.19R_6 - 0.18R_7$$

(Multiple correlation coefficient = 0.74)

$$Y_2 = 38.94 + 0.05X_1 - 0.02R_1 + 0.002R_2 + 1.67R_3 + 0.21R_4 + 0.06R_5 + 0.02R_6 - 0.69R_7$$

(Multiple correlation coefficient = 0.72)

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$$Y_3 = 3273.4 - 24.37X_1 + 9.997R_1 + 8.48R_2 - 268.68R_3 + 120.92R_4 + 67.27R_5 + 27.89R_6 - 138.46R_7$$

(Multiple correlation coefficient = 0.66)

To formulate this problem as a GP problem, the first setup required to be transformed to obtain one sided specification only, and these transformed variables are used in the GP formulation described. For example, the input-wood percentage (X_1) should be between 20 and 40. This is transformed as $X'_1 = X_1 - 20 \leq 20$, and in other variables as $R'_3 = R_3 - 2 \leq 2.4$, $Y'_3 = Y_3 \approx 5000$, and next setup modified regression equation for example: $Y'_1 = -0.334 + 0.06X'_1 - 0.05R'_1 + 0.004R'_2 - 0.67R'_3 + 0.24R'_4 - 0.13R'_5 + 0.19R'_6 - 0.18R'_7$

The Pre-emptive Priority factor is the K-number most important characteristic to be fulfilled gets the top priority. Priorities for others which in the fixed by the management after giving due consideration to the quality aspect as well as the ease of adjusting and modifying the levels of those variables. Sengupta (1981) has formulated the GP problem as follows:

$$\text{Minimize } Z = P_1\delta_{Y'_1}^- + P_2(\delta_{Y'_2}^- + \delta_{Y'_2}^+) + P_3(\delta_{Y'_3}^- + \delta_{Y'_3}^+) + P_4(\delta_{R'_4}^- + \delta_{R'_7}^-) \\ + P_5(\delta_{X'_1}^- + \delta_{R'_1}^- + \delta_{R'_2}^- + \delta_{R'_3}^- + \delta_{R'_5}^- + \delta_{R'_6}^-)$$

Subject to:

Output constraints:

$$Y'_1 + \delta_{Y'_1}^- = 2 \text{ i.e}$$

$$0.06X'_1 - 0.05R'_1 + 0.004R'_2 - 0.67R'_3 + 0.24R'_4 - 0.13R'_5 + 0.19R'_6 - 0.18R'_7 + \delta_{Y'_1}^- = 2.334$$

$$Y'_2 + \delta_{Y'_2}^- - \delta_{Y'_2}^+ = 35 \text{ i.e}$$

$$0.05X'_1 - 0.02R'_1 + 0.002R'_2 + 1.67R'_3 + 0.21R'_4 + 0.06R'_5 + 0.02R'_6 - 0.69R'_7 + \delta_{Y'_2}^- - \delta_{Y'_2}^+ = 0.6085$$

$$Y'_3 + \delta_{Y'_3}^- - \delta_{Y'_3}^+ = 5000 \text{ i.e}$$

$$24.37X'_1 + 9.997R'_1 + 8.48R'_2 - 268.68R'_3 + 120.92R'_4 + 67.89R'_5 - 27.89R'_6 - 138.46R'_7 + \delta_{Y'_3}^- - \delta_{Y'_3}^+ = 726.139$$

Input constraint

$$X'_1 + \delta_{X'_1}^- = 20$$

Process constraints

$$R'_1 + \delta_{R'_1}^- = 35; \quad R'_2 + \delta_{R'_2}^- = 33; \quad R'_3 + \delta_{R'_3}^- = 2.4; \quad R'_4 + \delta_{R'_4}^- = 12.5; \quad R'_5 + \delta_{R'_5}^- = 15;$$

$$R'_6 + \delta_{R'_6}^- = 12; \quad R'_7 + \delta_{R'_7}^- = 6.2;$$

With: $X'_1 \geq 0$; $R'_t \geq 0$, $t = 1, 2, \dots, 7$

The optimal solution is:

$$X_1 = 44; R_1 = 160; R_2 = 176; R_3 = 3; R_4 = 11.5; R_5 = 28; R_6 = 23 \text{ and } R_7 = 18.$$

This solution result in $Y_1 = 16.42$; $Y_2 = 35.43$ and $Y_3 = 5910$.

2-Fuzzy goal programming

Fuzzy set theory, introduced by Lotfi A. Zadeh (1965), provides an effective framework for handling imprecision. Within this context, an objective associated with an imprecise aspiration level can be represented as a fuzzy goal. Narasimhan (1980) was among the first to integrate fuzzy set theory into Goal Programming (GP), proposing a fuzzy goal programming (FGP) model. Subsequently, Hannan (1981) simplified Narasimhan's approach, reformulating it as an equivalent linear programming (LP) model. These foundational contributions stimulated extensive research into the development and application of FGP in real-world problems.

To address FGP problems, a variety of models based on different methodological approaches have been proposed. A comprehensive survey and classification of these models were provided by Chanas and Kuchta (2002). In general, three main types of fuzzy goals are commonly identified, and the FGP model presented here incorporates these categories.

$$\begin{aligned} OPT (AX)_i &\leq_{\approx} b_i \quad i = 1, \dots, i_0 \\ (AX)_i &\geq_{\approx} b_i \quad i = i_0 + 1, \dots, j_0 \\ (AX)_i &\cong \quad i = j_0 + 1, \dots, K \\ X &\in C_S, \end{aligned}$$

Where OPT means finding an optimal decision X such that all fuzzy goals are

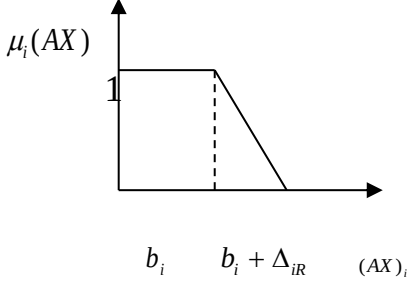
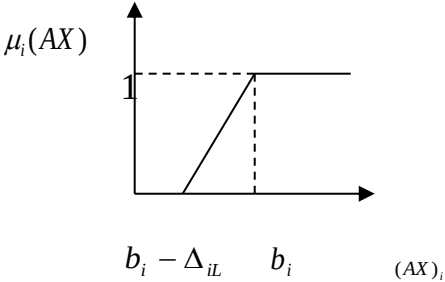
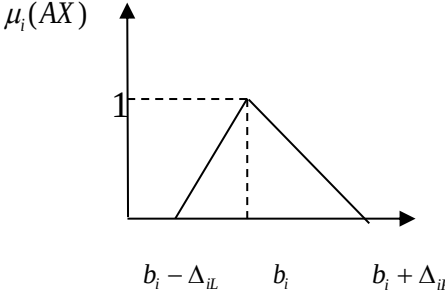
satisfied, $(AX)_i = \sum_{j=1}^n a_{ij} x_j \dots i = 1, \dots, k$, b_i is the aspiration level for i .th goal.

2-1 Membership functions

Narasimhan (1980) and Hannan (1981) were the first to formulate a fuzzy goal programming (FGP) model based on the concept of membership functions. These functions are defined over the interval $[0, 1]$, where the membership value for the i -th goal equals 1 when the goal is fully achieved, indicating complete satisfaction of the decision maker; otherwise, it takes a value between 0 and 1.

In both theory and practice, linear membership functions are more commonly used than other forms. For the four types of fuzzy goals mentioned above, linear membership functions can be defined and illustrated as shown in Fig. 2.

Fig.1. A type of linear membership functions

Membership function	Analytical definition
	$\mu_i(AX)_i = \begin{cases} 1 & \text{if } (AX)_i \leq b_i \\ \frac{(AX)_i - b_i}{\Delta_{iR}} & \text{if } b_i \leq (AX)_i \leq b_i + \Delta_{iR} \\ 0 & \text{if } (AX)_i \geq b_i + \Delta_{iR} \end{cases} \quad i = 1, \dots, i_0 \dots (1)$
Type 1	
	$\mu_i(AX)_i = \begin{cases} 1 & \text{if } (AX)_i \geq b_i \\ \frac{b_i - (AX)_i}{\Delta_{iL}} & \text{if } b_i - \Delta_{iL} \leq (AX)_i \leq b_i \\ 0 & \text{if } (AX)_i \leq b_i - \Delta_{iL} \end{cases} \quad i = i_0 + 1, \dots, j_0 \dots (2)$
Type 2	
	$\mu_i(AX)_i = \begin{cases} 0 & \text{if } (AX)_i \leq b_i - \Delta_{iL} \\ \frac{(AX)_i - b_i - \Delta_{iL}}{\Delta_{iL}} & \text{if } b_i - \Delta_{iL} \leq (AX)_i \leq b_i \\ \frac{b_i - (AX)_i}{\Delta_{iR}} & \text{if } b_i \leq (AX)_i \leq b_i + \Delta_{iR} \\ 0 & \text{if } (AX)_i \geq b_i + \Delta_{iR} \end{cases} \quad i = j_0 + 1, \dots, k_0 \dots (3)$
Type 3	

Source: Authors' own elaboration.

2-2 FGP based on Hannan approach

The incorporation of membership functions into Goal Programming (GP) was first introduced by Narasimhan (1980), and subsequently extended by Hannan (1981a, b), Ignizio (1982), and Tiwari et al. (1987). Compared with Narasimhan's formulation, the FGP model proposed by Hannan (1981a, b) is considered simpler and more efficient. In this model, the aspiration levels are treated as fuzzy.

This fuzziness is represented using a triangular membership function defined over the interval [0, 1]. The mathematical formulation of Hannan's (1981) model is presented as follows:

$$\text{Max } Z = \mu$$

subject to :

$$f_i(x)/\Delta_i + \delta_i^- - \delta_i^+ = g_i/\Delta_i \quad (\text{for } i = 1, 2, \dots, p) \dots\dots\dots(1)$$

$$\lambda + \delta_i^- + \delta_i^+ \leq 1 \quad (\text{for } i = 1, 2, \dots, p) \dots\dots\dots(2)$$

$$x \in X \dots\dots\dots(3)$$

$$\lambda, \delta_i^- \text{ and } \delta_i^+ \geq 0 \dots\dots\dots(4)$$

where Δ_i is the constant of deviation of the aspiration levels g_i . This constant is specified by the DM. This formulation incorporates an equivalent linear membership function type 3 fig3 were $\Delta_{ir} = \Delta_{il} = \Delta_i$.

Hannan(1981) proposed an alternative formulation in the FGP based on weighted FGP (WFGP) this formulation introduced nonfuzzy relative importance coefficients w_i^+ and w_i^- associated with the positive and the negative deviations, respectively. These weights reflect, partially, the importance that the DM can express differently depending on whether there is an over or under achievement of the objective. The WFGP formulation is as follows:

$$\text{Min } Z = \sum_{i=1}^p (w_i^- \delta_i^- + w_i^+ \delta_i^+)$$

Subject to :

constraint 1 – 3

3-FGP for designing a QCS using Hannan approach

To deal with FGP problems some models use the concept of deviational variables in GP. These models try to minimize an additive summation of deviations from imprecise aspiration levels of fuzzy goals. Hannan (1981) introduced the first formulation in the FGP his model is only isosceles triangular linear membership function (Fig1-type3) which considered, ($\Delta_{il} = \Delta_{ir}$) indicates both left and right admissible violations for the i th fuzzy goal. δ_i^- and δ_i^+ , Hannan (1981) proposed two approaches in the FGP (Minmax approach and Additive approach), the first approach Maximizes the degree of membership functions and the seconds Minimizes an additive summation of deviations. The application of two objective functions to Hannan (1980) for designing the QCS in the paper factory is as follows:

Minmax approach: maximize degree of memberships functions μ_i its model is as follows:

$$\text{Max } z = \mu$$

subject to

$$-0,06X_1 + 0,05R_1 - 0,004R_2 + 0,67R_3 - 0,24R_4 + 0,13R_5 - 0,19R_6 + 0,18R_7 - \delta_{y_1}^- + \delta_{y_1}^+ = 5,84 \quad (4)$$

$$-0,025X_1 + 0,01R_1 - 0,001R_2 - 0,835R_3 - 0,105R_4 - 0,03R_5 - 0,01R_6 + 0,345R_7 - \delta_{y_2}^- + \delta_{y_2}^+ = 1,97 \quad (5)$$

$$-0,0812X_1 + 0,033R_1 + 0,028R_2 - 0,895R_3 + 0,403R_4 + 0,224R_5 + 0,092R_6 - 0,461R_7 - \delta_{y_3}^- + \delta_{y_3}^+ = 5,753 \quad (6)$$

$$0,1X_1 + \delta_{x_1}^- - \delta_{x_1}^+ = 3 \quad (7)$$

$$0,0571 + \delta_{R_1}^- - \delta_{R_1}^+ = 9 \quad (8)$$

$$0,0606R_2 + \delta_{R_2}^- - \delta_{R_2}^+ = 9,485 \quad (9)$$

$$0,833R_3 + \delta_{R_3}^- - \delta_{R_3}^+ = 2,666 \quad (10)$$

$$0,16R_4 + \delta_{R_4}^- - \delta_{R_4}^+ = 2,28 \quad (11)$$

$$0,133R_5 + \delta_{R_5}^- - \delta_{R_5}^+ = 3,666 \quad (12)$$

$$0,166R_6 + \delta_{R_6}^- - \delta_{R_6}^+ = 3,166 \quad (13)$$

$$0,322R_7 + \delta_{R_7}^- - \delta_{R_7}^+ = 5,032 \quad (14)$$

$$\mu + \delta_{y_i}^- + \delta_{y_i}^+ \leq 1 \quad (15)$$

$$\mu + \delta_{x_1}^- + \delta_{x_1}^+ \leq 1 \quad (16)$$

$$\mu + \delta_{R_t}^- + \delta_{R_t}^+ \leq 1 \quad (17)$$

$$\mu, \delta_{y_i}^-, \delta_{y_i}^+, \delta_{x_1}^-, \delta_{x_1}^+, \delta_{R_t}^-, \delta_{R_t}^+, Y_i, X_1 \text{ and } R_t \geq 0 \text{ (For } i = 1, 2, 3 \text{ and } t = 1, 2, \dots, 7). \quad (15)$$

Using the LINGO package, the obtained optimal solution is as follows:

$$X_1 = 35,886, R_1 = 147,197, R_2 = 145, R_3 = 3,04, R_4 = 10,57, R_5 = 22,249, R_6 = 22,249, R_7 = 18,152$$

This solution results in to $Y_1 = 16,455, Y_2 = 36,177, Y_3 = 5229,926$.

Additive approach: minimize a additive summation of deviations: the objective function and constraints in their model is as follows:

$$\text{Minimize } Z = \sum_{i=1}^3 (\delta_{y_i}^- + \delta_{y_i}^+) + \sum_{j=1}^1 (\delta_{x_j}^- + \delta_{x_j}^+) + \sum_{t=1}^7 (\delta_{R_t}^- + \delta_{R_t}^+)$$

Subject to: Constraints (4)-(17).

the optimal solution is as follows: $X_1 = 36,288, R_1 = 139,99, R_2 = 156,502, R_3 = 3,2, R_4 = 11,605, R_5 = 20, R_6 = 18,99, R_7 = 18,302$ This solutions is yielding to $Y_1 = 17,04, Y_2 = 35, Y_3 = 5056,82$

The Comparison between FGP to QCS model presented in this study and sengupta approach indicated in Table 3.

Use of models FGP-QCS will depend largely on the goodness of the regression model because If the relationship between input characteristics, output characteristics and process parameters is week then the solution may deviate from the optimum, and depend also on type of membership functions.

Table 2. Comparisons between major QCS models

	variables	Target intervals	Sengupta approach	Hannan Approach	
				MINMAX Approach	ADDITIVE Approach
Input characteristics	(X_1)	[20, 40]	44	35,886	36,288
Process variables	(R_1)	[140, 175]	160	147,197	139,99
	(R_2)	[140, 173]	176	146,789	156,502
	(R_3)	[2, 0, 4, 4]	3	3,634	3,2
	(R_4)	[8, 0, 20, 5]	11,5	10,570	11,605
	(R_5)	[20, 35]	28	23,085	20
	(R_6)	[13, 25]	23	22,249	18,99
	(R_7)	[12, 5, 18, 7]	18	17,429	18,302
Output characteristics	(Y_1)	[16, 18]	16,42	16,455	17,04
	(Y_2)	Close to 35	35,43	36,177	35
	(Y_3)	Close to 5000	5910	5229,926	5056,86

Source: Authors' own elaboration.

4- Conclusions

The design of a quality control system (QCS) primarily involves determining the appropriate levels of input and process variables in order to satisfy predefined output specifications. Given the complexity of real-world industrial environments, where uncertainty and imprecision are inherent, such problems can be effectively addressed within the framework of imprecise Goal Programming (GP), particularly through fuzzy goal programming (FGP) models.

In this study, two alternative formulations for QCS design have been developed based on the FGP approach originally proposed by Hannan (1981). These formulations incorporate triangular linear membership functions to represent the fuzziness associated with aspiration levels and decision-maker preferences. The first formulation focuses on maximizing the degree of satisfaction by enhancing the membership levels of the goals, while the second formulation seeks to minimize the aggregated deviations from the desired targets. Together, these approaches provide flexible and realistic tools for handling multi-objective decision-making problems in the presence of uncertainty.

The proposed models were implemented and solved using LINGO software, which facilitated the computation of optimal solutions in an efficient and structured manner. The results obtained demonstrate the capability of the models to determine suitable levels of input and process variables that meet the required output specifications. Moreover, the application to the paper industry, based on the example originally developed by Sengupta (1981), confirms the

practical relevance and applicability of the proposed formulations in real industrial settings. The models also offer decision makers a structured framework to balance multiple conflicting objectives while accounting for imprecision in system parameters.

However, the performance and reliability of the proposed approach are closely linked to the quality of the regression models used to establish relationships between input variables, process variables, and output characteristics. If these relationships are not accurately estimated, the resulting solutions may be suboptimal or may fail to reflect the true behavior of the system. This limitation highlights the importance of robust modeling techniques in capturing the underlying dynamics of the production process.

In addition, the current study assumes linear relationships and relies on predefined membership functions, which may not always fully capture the complexity of real-world systems. Future research could address these limitations by exploring non-linear formulations, alternative types of membership functions, and more advanced optimization techniques. In particular, the integration of fuzzy regression models, such as the approach developed by Hassanpour et al. (2009), could provide a more accurate and flexible representation of the relationships among input, process, and output variables. Such an extension would enhance the robustness of the model and improve its ability to deal with uncertainty and data imprecision.

Furthermore, future studies may consider hybrid approaches that combine FGP with other multi-criteria decision-making methods, as well as the incorporation of dynamic or stochastic elements to better reflect changing industrial environments. Expanding the application of the proposed models to other industries and comparing their performance with alternative optimization techniques would also provide valuable insights. Overall, the proposed formulations represent a meaningful step toward improving QCS design under uncertainty, while offering several avenues for further development and refinement.

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