*Nigerian Journal of Technology (NIJOTECH)*
*Vol. 45, No. 1, March 2026, pp. 35- 45*
www.nijotech.com

*Print ISSN: 0331-8443*
*Electronic ISSN: 2467-8821*
https://doi.org/10.4314/njt.2026.5565

# A SYSTEMATIC FRAMEWORK FOR FEASIBILITY EVALUATION IN WELDING FLUX DEVELOPMENT

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**ARTICLE HISTORY:**
**Received:** September 03, 2025.
**Revised:** February 25, 2026.
**Accepted:** February 26, 2026.
**Published:** April 29, 2026.

**KEYWORDS:**
Feasible criterion space, Flux quality attributes, Multi-objective optimization, Pareto front, Welding consumable

**ARTICLE INCLUDES:**
Peer review

**DATA AVAILABILITY:**
On request from author(s)

**EDITORS:**
Ozoemena Ani

**FUNDING:**
None

## Abstract

*The long lead time and resource consumption associated with the traditional trial-and-error method have been a significant challenge in welding flux design (WFD). The methods for assessing feasibility early in the WFD process before committing significant resources to experimentation are limited. This study presents a systematic framework for evaluating the feasibility of achieving targeted welding flux quality attribute (WFQA) levels, thereby enabling more efficient and informed WFD decisions. Response models, multi-criteria optimization, and Pareto fronts analysis were integrated to delineate the feasible WFQA space. Unlike prior optimization-based approaches, the proposed framework explicitly delineates the feasible WFQA space, thereby integrating feasibility evaluation into the design process and enabling upfront assessment of whether targeted attribute levels are achievable prior to experimentation. This space was subsequently employed for a priori evaluation of the feasibility of a bi-attribute WFD scenario with silicon and manganese transfer* $(\Delta Si, \Delta Mn)$ *as quality attributes. The feasibility of developing six welding fluxes (A-F), with targeted* $(\Delta Si, \Delta Mn)$ *values: A(0.11%, 0.15%), B(0.07%, 0.26%), C(0.17%, 0.30%), D(0.08%, 0.28%), E(0.16%, 0.04%), F(0.20%, 0.14%) was determined by evaluating whether these values lie within the defined WFQA space. Fluxes B, D, and E were found to be unattainable within the current WFD domain, thereby preventing the excessive consumption of time and resources on infeasible WFQA targets. Future work should focus on extending the framework to multi-attribute systems, particularly those with non-convex Pareto fronts.*

## 1.0 INTRODUCTION

Welding is an enabling process across a spectrum of industries, including manufacturing, construction, shipbuilding, aerospace, petrochemical, automotive, nuclear, and cryogenic applications. Arc welding is the most commonly used welding method in these industries. The quality, reliability, and fulfillment of the service performance requirements of the welded structure and components depend on the welding process parameters. They also depend on the materials used during welding. Welding consumables, such as filler metals and flux, play a crucial role in ensuring efficient welding operations and high-performance welded structures. To meet the continuous improvement needs of various industries, new materials are being developed at an unprecedented rate. Most of these materials are

***HOW TO CITE:***
Adeyeye, A. D. "A Systematic Framework for Feasibility Evaluation in Welding Flux Development", *Nigerian Journal of Technology*, 2026. 45(1), pp. 35 - 45. https://doi.org/10.4314/njt.2026.5565

designed to be weldable and require the development of appropriate welding consumables to enhance their rapid deployment [1] - [6]. Despite increased research activity, welding consumable development has yet to keep pace with advances in new materials, thereby hampering their rapid deployment.

Arc welding technology has received much attention, especially in the areas of mitigating the long lead time in welding wires and flux development. The development of welding wires is a time- and resource-intensive process owing to metallurgical, mechanical, and manufacturability demands as well as the need for extensive experimentation. This process involves steel/alloy design, alloy making, casting, rolling, and wire drawing, with an intermediate heat treatment before the final wire is produced. Although both welding wire and flux require extensive experimentation during development, welding wires are more expensive than welding flux because their production consumes more time, materials, and energy [6]-[9]. Owing to the high cost of welding wires, welding consumable designers often opt to design a different flux while retaining the original wire or using a more affordable wire, thereby reducing overall production expenses. This allows the same wire to be used to weld different metals or achieve different weld deposits. Rahul *et al*. [10] developed cost-effective and environmentally benign electrodes using a more affordable mild steel wire in place of a costly stainless steel wire for welding 304 and 316 grade stainless steels. When paired with the designed flux, the mild steel core wire deposited weld metal with mechanical and corrosion-resistant properties comparable to those of stainless steel core wire electrodes. Although the cost of welding flux development is lower than that of wires, reducing the long lead times and the costly, and time-intensive experimentation involved remains essential.

Many efforts have been made to reduce the welding flux lead time and the consumption of materials and energy during trial and test experiments [11]-[15]. Prior to 2004, welding flux development relied primarily on trial-and-error experiments. Kanjilal *et al*. [12] were among the first to apply statistical design of experiments (DoE) in Welding Flux Design (WFD). The DoE employed is a mixture design. This approach reduces the number of experiments and time, which consequently reduces the lead time, and resource consumption such as materials and energy. This method provides reliable information and insights from fewer experiments, optimally covers the welding flux composition space, and eliminates bias. Mixture experiments have become popular and are being used by welding flux researchers because of their benefits [16] - [22]. The benefits of DoE, as demonstrated by Kanjilal *et al*. [12], have spurred researchers to explore other DoE methods. For example, Nwigbo *et al*. [23], [24] used a central composite design, while Ren *et al*. [13] used a uniform design. Achebo [25] used a Hadamard multivariate design, whereas Achebo [26] used a nested experimental design. The Taguchi method and response surface method coupled with principal component analysis and gray relational analysis have also been used [27] - [29].

Regression models have also been developed to predict welding flux quality characteristics and further reduce lead time and resource consumption. Nwigbo *et al*. [23] developed a regression model for predicting tensile strength as a function of flux ingredients. Similarly, Sharma *et al*. [19] developed models for predicting weld metal chemical composition and element transfer while Gupta *et al*. [21] developed models for predicting tensile strength, elongation, impact strength, and micro hardness. The models also provide insights into how the flux ingredients interact to determine the required welding flux quality characteristics, such as the direction and magnitude of these interactions. However, these models are limited to binary interactions. Sharma and Chhibber [16], [17] advanced the models to include ternary interactions. Mishra *et al*. [18] and Kumar and Chhibber [30] used artificial neural networks to predict physicochemical properties and element transfer, respectively. Adeyeye *et al*. [31] developed models that incorporated edge effects to predict quality characteristics that Kanjilal *et al*. [12] could not adequately predict.

Adeyeye and Oyawale [32], [33] proposed goal programming models to prescribe flux ingredient proportions that provide the best balance among welding flux quality attributes (WFQAs). The desirability function has also been used to optimize the welding flux properties [16], [17], [28], [34]-[37]. Adeyeye and Allu [38] used compromise programming, whereas Singh *et al*. and Irechukwu *et al*. [39, 40] coupled the response surface method, principal component analysis, and grey relational analysis for multi-objective optimization of the welding flux. Adeyeye and Osinubi [41] developed a framework for incorporating stakeholders' preferences into the optimization process and trade-off analysis. The application Design of Experiment (DoE), predictive modelling, and optimization techniques has mitigated challenges such as long lead


https://doi.org/10.4314/njt.2026.5565

times, costly experimentation, and variability in achieving desired flux properties [42].

Furthermore, the interactions among the flux components were identified and quantified to the optimum flux was obtained. However, these optimization-based methods do not provide a feasibility evaluation of the targeted flux quality attributes. The proposed framework advances beyond optimization by explicitly integrating feasibility assessment, thereby allowing flux designers to identify unattainable attribute targets before committing resources.

To some extent, these models and approaches have helped mitigate the drawbacks associated with extensive and time-intensive trial and test procedures. However, when a new welding flux is needed, either to weld a different metal or to deposit a weld metal with different properties, a lengthy and costly process must be initiated. This is because the flux formulator cannot determine *a priori* whether the desired performance level or quality target is achieveable. Frequently, significant time and resources are expended on lengthy experiments before it is realized that the targeted attribute performance levels are infeasible. There is a need for a method of identifying feasibility before the commitment of resources to experimentation. Therefore, it is imperative to develop a framework to establish feasibility. This study addresses this challenge by introducing a systematic approach for identifying the feasible flux quality space, thereby enabling the flux designer determine a priori whether the desired flux quality targets are achievable before committing resources to the venture.

## 2.0 METHOD

Consider a WFD situation in which a new and cost-effective welding consumable is required to weld a different metal or deposit a weld metal with different quality attribute targets. The WFD environment is defined as follows: (1) the new welding flux is to be formulated for the existing welding wire using the same welding flux ingredients (2) the new welding flux is to be used under the same welding and operational conditions as those used to develop the existing flux (3) the WFQAs the new welding flux is expected to achieve is the same set of WFQAs or a subset of the existing flux attributes but at different target levels (4) the technical constraints and prediction equations for the WFQAs are still valid for the new flux. The problem is how to determine, *a priori*, whether the same welding flux ingredients can be formulated to weld the new metal or meet the desired quality targets before embarking on the flux development process. The feasibility of the new flux is determined as follows:

Step 1: Identification of relevant WFQAs: The WFQAs are determined based on the desired operational characteristics and weld metal properties the new flux is expected to achieve. In addition, the desired target levels or directions of optimization for each quality attribute must also be established.

Step 2: Identify the response functions, $\mathrm{f_i}(\mathrm{x_k})$ developed for predicting the WFQAs during the formulation of the existing flux as well as the ingredients and their respective upper and lower limits. The indices $i \; and \; k$ represent WFQA and flux ingredients respectively. State-of-the-art welding flux development involves experimental design and formulation of response functions. The functions developed during the formulation of the existing welding flux are required for the formulation of the new flux. The procedure for developing the response functions is well documented in the literature and is therefore not detailed here [11], [12], [14], [16]-[23].

Step 3**:** Suppose a set (*I*) of WFQAs with their respective response functions, $\mathrm{f_i}(x_k)$ has been identified in steps 1 and 2. Convert each $\mathrm{f_i}(x_k)$ to its normal form, $\mathrm{f_i^N}(x_k)$ as shown in Equation (1).

Normalization is necessary because the WFQAs often have different units and the coefficients of the terms of $\mathrm{f_i}(x_k)$ are in different orders of magnitude.

Normalization converts the functions to dimensionless and ensures that no WFQA function dominates the other [42].

$$\mathrm{f_i^N}(x_k) = \left(\frac{\mathrm{w_i}}{\sqrt{\sum_{j \in J} \mathrm{c_{ij}^2}}}\right) \mathrm{f_i}(x_k); \text{ for each } \mathrm{i} \in \mathrm{I} \qquad (1)$$

Where, $x_k$ is the proportion of flux ingredient k, $\mathrm{w_i}>0, \forall \mathrm{i}$ and $\sum i \in I \; w_i=1$, is the weight of each WFQA $\mathrm{i} \in \mathrm{I}$, while $c_{ij}$ is the coefficient of the $j^{th}$ term of the WFQA function [41].

Step 4: Convert minimizing objectives to maximizing objectives and linearly combine them to form one function ($\mathrm{F}(x_k)$) using Equation (2).


https://doi.org/10.4314/njt.2026.5565

$$F(x_k) = \sum i \in I \left( \frac{w_i}{\sqrt{\sum_{j \in J} c_{ij}^2}} \right) f_i(x_k) \quad (2)$$

Step 5: The technical constraints consisting of a set (K) relevant flux ingredients with their respective lower ($L_k$) and upper ($U_k$) limits in terms of their proportions in the flux is added to Equation (2) to develop the optimization model in Equation (3).

$$\text{Maximize } F(x_k) = \sum i \in I \left( \frac{w_i}{\sqrt{\sum_{j \in J} c_{ij}^2}} \right) f_i(x_k)$$

Subject to;

$L_k = x_k = U_k$, for each $k \in K$

$\sum_{k \in K} x_k$ =, or < 100% (3)

The first constraint in Equation (3) imposes lower and upper bounds on the ingredient proportions, as dictated by flux formulation technology. The second constraint enforces mass balance: the proportions of variable-composition ingredients sum to 100% when no fixed additives are present, and to less than 100% when fixed-proportion materials (e.g. binders and ferroalloys) are included. Finally, the model in Equation. (3) is solved as a weighted-sum optimization problem using appropriate optimization software. Different weight structures (i.e. values of $w_i$) are used to approximate the Pareto fronts which are then combined to define the feasible attribute space of the WFOAs. The synthesis of Pareto fronts is not only used for optimization but also serves as the basis for feasibility evaluation. By delineating the feasible attribute space, the framework enables a priori assessment of whether the specified flux quality targets lie within or outside the achievable domain.

## 3.0 ILLUSTRATIVE EXAMPLE

### 3.1 Description of the Problem

This section illustrates how the information on the existing flux can be used to establish the feasibility of achieving the desired flux quality attribute levels for a new flux using secondary data from Kanjilal *et al.* [11]. The details of the existing submerged arc welding flux by Kanjilal *et al.* [11]; the specific ingredients and their respective upper and lower bounds are presented in Table 1 while the filler wire and base metal compositions are presented in Table 2. Based on the technology of flux development, the proportion of four out of the ingredients in the flux can be varied by the flux designer and they accounted for 80% of the total flux composition, while the remaining 20% was composed of ingredients with a constant composition. The welding parameters were current 400A, voltage 26V, and welding speed of 4.64mm/sec. The response functions for the WFQAs in terms of flux ingredient proportions for the existing flux are presented in Equations. (2) and (3) [11]. Consider a situation where a new flux is needed to achieve specified levels of the WFQAs and the flux designer wants to know upfront if the specified levels are attainable before committing efforts and resources to the flux formulation process. Two WFQAs, silicon transfer ($\Delta Si$) and manganese transfer ($\Delta Mn$), were selected to illustrate the approach with their response functions presented in Equations 4 and 5 [11]. Four bi-attribute cases presented in Table 3 were used to determine the feasible WFQA space described in Section 2 with $f_{Si}(x)$ and $f_{Mn}(x)$ as the objectives of the optimization problem.

$$F_{si}(x) = 0.012176x_{CaO} + 0.0556335x_{MgO} + 0.006303x_{CaF2} + 0.013559x_{Al2O3} - 0.001364x_{CaO}x_{MgO} - 0.000063x_{CaOCaF2} - 0.000190x_{CaO}x_{Al2O3} - 0.001332x_{MgO}x_{CaF2} - 0.001429x_{MgO}x_{Al2O3} + 0.000220x_{CaF2}x_{Al2O3} \quad (4)$$

where $x_{CaO}$, $x_{MgO}$, $x_{CaF_2}$ and $x_{Al_2O_3}$ represent the proportions of $CaO$, $MgO$, $CaF_2$ and $Al_2O_3$ respectively.

$$F_{MN}(x) = -0.029867x_{CaO} + 0.05574x_{MgO} - 0.004323x_{CaF2} - 0.002228x_{Al2O3} - 0.000474x_{CaO}x_{MgO} + 0.001225x_{CaO}x_{CaF2} + 0.001361x_{MgO}x_{Al2O3} - 0.001352x_{MgO}x_{CaF2} - 0.001532x_{MgO}x_{Al2O3} + 0.000204x_{CaF2}x_{Al2O3} \quad (5)$$

**Table 1**: Lower and upper bounds of ingredients

| **Flux ingredients** | **Variable Composition (wt%)** | | | | **Constant Composition (wt%)** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CaO$ | $MgO$ | $CaF_2$ | $Al_2O_3$ | $SiO_2$ | $Fe\text{-}Mn$ | $Fe\text{-}Si$ | $Ni$ | **Bentonite** |
| Lower bound | 15.00 | 10.00 | 10.00 | 8.00 | 10.00 | 4.00 | 3.00 | 1.00 | 2.00 |
| Upper bound | 35.00 | 32.40 | 40.00 | 40.00 | | | | | |

**Source**: Extracted from [11]


https://doi.org/10.4314/njt.2026.5565

**Table 2**: Filler wire composition

| **Element** | **C (wt.%)** | **Mn (wt.%)** | **Si (wt.%)** | **S (wt.%)** | **P (wt.%)** | **Ni (wt.%)** | **O (ppm)** | **N (ppm)** |
|---|---|---|---|---|---|---|---|---|
| Base metal | 0.22 | 0.77 | 0.25 | 0.03 | 0.02 | - | 350 | 50 |
| Filler wire | 0.102 | 0.561 | 0.050 | 0.022 | 0.011 | - | 380 | 60 |

**Source**: [11]

## 3.2 Model Development

### 3.2.1 Constraints of the problem

Flux ingredient constraints concerning the limits on the ingredients are developed based on Table 1. The respective constraints for $CaO$, $MgO$, $CaF_2$ and $Al_2O_3$ are presented in Equations. (6) - (9)

$$15 = x_{CaO} = 35 \qquad (6)$$

$$10 = x_{MgO} = 32.40 \qquad (7)$$

$$10 = x_{CaF_2} = 40 \qquad (8)$$

$$8 = x_{Al_2O_3} = 40 \qquad (9)$$

The technology of the flux formulation problem requires that the variable ingredients, sum up to 80% of the total flux composition Equation. (10).

$$x_{CaO} + x_{MgO} + x_{CaF_2 +} x_{Al_2O_3} = 80 \qquad (10)$$

### 3.2.2 Objectives of the problem

The silicon and manganese transfer functions (Equations (4) and (5)) were normalized using Equation (1). The normal forms of $f_{Si}(\text{x})$ and $f_{Mn}(x)$ respectively are $\text{f}_{\text{Si}}^{\text{N}}(\text{x})$ and $\text{f}_{\text{Mn}}^{\text{N}}(\text{x})$ as presented in Equations. (11) and (12).

$$f_{si}^{N}(\text{x}) = \left(\frac{w_{Si}}{0.058930872}\right)(0.012176x_{CaO} + 0.055635x_{Mgo} + 0.006303x_{CaF_2} + 0.013559x_{Al_2O_3} - 0.001364x_{CaO}x_{MgO} - 0.000063x_{CaO}x_{CaF_2} - 0.000190x_{CaO}x_{Al_2O_3} - 0.001332x_{MgO}x_{CaF_2} - 0.001429x_{MgO}x_{Al_2O_3} + 0.000220x_{CaF_2}x_{Al_2O_3}) \qquad (11)$$

$$\text{f}_{\text{Mn}}^{\text{N}}(x) = \left(\frac{\text{w}_{\text{Mn}}}{0.063485682}\right)(-0.029867x_{CaO} + 0.05574x_{MgO} - 0.004323x_{CaF_2} - 0.002228x_{Al_2O_3} - 0.000474x_{CaO}x_{MgO} + 0.001225x_{CaO}x_{CaF_2} + 0.001361x_{CaO}x_{Al_2O_3} - 0.001352x_{MgO}x_{CaF_2} - 0.001532x_{MgO}x_{Al_2O_3} + 0.000204x_{CaF_2}x_{Al_2O_3}) \qquad (12)$$

where $\text{w}_{\text{Si}}, \text{w}_{\text{Mn}} > 0$; and $\text{w}_{\text{Si}} + \text{w}_{\text{Mn}} = 1$

To define the feasible attribute space, all possible combinations of the bi-attribute optimization directions were considered (see Table 3). Equations (11) and (12) were converted to the same form and linearly combined. For instance, in Case 1 the manganese transfer minimization objective was transformed into a maximization objective by multiplying it by -1. Hence the complete model for Case 1 after conversion and combination is as expressed in Equation. 13. The coefficients of the combined objective function Equation. (13) are influenced by the weight structure. To ensure a neutral and systematic exploration of the trade-offs between objectives, weight vectors were generated by sampling the admissible simplex (non-negative weights summing to one). The weights were varied across their feasible range to provide reproducible coverage of the objective trade-off space. Under the weighted-sum formulation, each admissible weight vector yields a candidate Pareto-optimal solution; thus, systematic sampling enables approximation of the Pareto front without imposing systematic bias toward any particular objective. Each time a different weight vector from the admissible simplex was selected, the weighted sum was recalculated. Because normalization and linear combination of objectives must be performed for each new weight vector, a LINGO program was written to automate these steps (see Appendix). Finally, the the models were implemented in LINGO optimization software (LINGO 21.0.33) and solved using seven different weight structures for each of the four cases to generate non-dominated solutions that form the Pareto frontier.

$$\text{Maximize, } F_{MnSi}(x) = f_{Si}^{N}(x) + \left(-f_{Mn}^{N}(x)\right)$$

Subject to: $15 \leq x_{CaO} \leq 35$ ; $10 \leq x_{MgO} \leq 32.40$ ; $10 \leq x_{CaF_2} \leq 40$ ; $8 \leq x_{Al_2O_3} \leq 40$; $x_{CaO} + x_{MgO} + x_{CaF_2} + x_{Al_2O_3} = 80$ (13)

**Table 3**: Direction of optimization

| Quality Attributes | Optimization Direction | | | |
|---|---|---|---|---|
| | **Case 1** | **Case 2** | **Case 3** | **Case 4** |
| Silicon transfer ($\Delta Si$) | maximize | maximize | minimize | minimize |
| Manganese transfer ($\Delta Mn$) | minimize | maximize | minimize | maximize |

Following optimization, feasibility evaluation was conducted by integrating the Pareto frontiers. This step ensures that the feasible WFQA space is explicitly defined and provides a basis for assessing the attainability of the targeted flux designs. This space was subsequently employed for a priori assessment of feasibility of developing six welding fluxes (A - F). For each flux, the specific target values for the element transfer functions were set, corresponding to the coordinate ($\Delta Si, \Delta Mn$). The targets were: A (0.11%, 0.15%), B (0.07%, 0.26%), C (0.17%, 0.30%), D (0.08%, 0.28%), E (0.16%, 0.04%), F (0.20%, 0.14%). Feasibility was determined by evaluating whether these values lie within the defined WFQA space.

## 4.0 RESULTS AND DISCUSSION

### 4.1 Non-dominated Solution

The WFQA values obtained for $f_{Si}(x)$ and $f_{Mn}(x)$ in the four cases are presented in Table 4. A dominance checks confirmed that no single attribute value dominated the others across all the four cases. The numerical values represent the optimal trade-off where an improvement in one attribute can only be achieved at the expense of the other. It is useful for trade-off analysis when the flux designer is interested in any of the four cases.

**Table 4**: Numerical representation of pareto frontiers

| **Case 1** | | **Case 2** | | **Case 3** | | **Case 4** | |
|---|---|---|---|---|---|---|---|
| **Maximize,** $f_{Si}(x)$ | **Minimize,** $f_{Mn}(x)$ | **Maximize** ,$f_{Si}(x)$ | **Maximize,** $f_{Mn}(x)$ | **Minimize,** $f_{Si}(x)$ | **Minimize,** $f_{Mn}(x)$ | **Minimize,** $f_{Si}(x)$ | **Maximize** , $f_{Mn}(x)$ |
| 0.01671 | 0.00383 | 0.15764 | 0.30320 | 0.01671 | 0.00383 | 0.15764 | 0.30320 |
| 0.10515 | 0.02008 | 0.17202 | 0.30218 | 0.01572 | 0.00394 | 0.15435 | 0.30272 |
| 0.13667 | 0.03839 | 0.17268 | 0.30188 | 0.01497 | 0.00429 | 0.15203 | 0.30173 |
| 0.22301 | 0.10905 | 0.17293 | 0.30166 | 0.01468 | 0.00454 | 0.15092 | 0.30074 |
| 0.22917 | 0.12135 | 0.17314 | 0.30137 | 0.01445 | 0.00484 | 0.02665 | 0.15827 |
| 0.23084 | 0.12651 | 0.23112 | 0.13201 | 0.01415 | 0.00559 | 0.02360 | 0.14951 |
| 0.23131 | 0.13013 | 0.23131 | 0.13013 | 0.01406 | 0.00652 | 0.01406 | 0.00652 |

### 4.2 Feasible WFQA Space and Feasibility Assessment

A visual representation of the Pareto front for each case is presented in Figures 1-4. The Pareto front represents the boundary between the attainable and unattainable attribute values. Each of the figures (Figures 14) defines the boundary of a portion of the WFQA space.

Figure 1 (Case 1) illustrates the sharp conflicts between maximizing $\Delta Si$ and minimizing $\Delta Mn$. As $\Delta Si$ increases, $\Delta$ $Mn$ rises significantly, with the penalty becoming prohibitive beyond 0.22% $\Delta Si$, where further $\Delta Si$ gains incur disproportionately high $\Delta Mn$ expense. Figure 2 (Case 2) shows that under simultaneous minimization, $\Delta Mn$ remains relatively constant over a narrow initial regime (0.18- 0.19% $\Delta Si$), suggesting a neutral zone up to the knee-point.


https://doi.org/10.4314/njt.2026.5565

Beyond 0.19% $\Delta Si$, a sharp descent occurs, indicating a transition to conflicting WFQAs where improvements in $\Delta Si$ are achieved only at the expense of $\Delta Mn$. Figure 3 (Case 3) presents a convex trade-off in ssimultaneous minimization. Reductions in $\Delta Mn$ necessitate increases in $\Delta Si$ with the curve flatten after 0.004% $\Delta Mn$. Figure 4 (Case 4) highlights the interplay between minimizing $\Delta Si$ and maximizing $\Delta Mn$. Initially, $\Delta Mn$ gains between 0.01-0.15% are accompanied by negligible increase in $\Delta Si$, suggesting minimal conflict. Beyond 0.15% $\Delta Mn$, however, the relationship becomes a sharp conflicting, with higher $\Delta Mn$ values intrinsically linked to elevated (worse) $\Delta Si$ levels. The observed patterns are in agreement with previous reports [43].

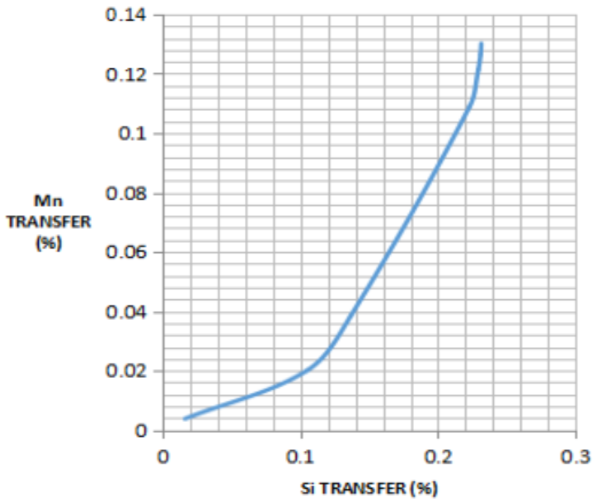


**Figure 1**: Pareto front visualization for case 1: (maximize ($F_{st}$) minimize ($F_{Mn}$))

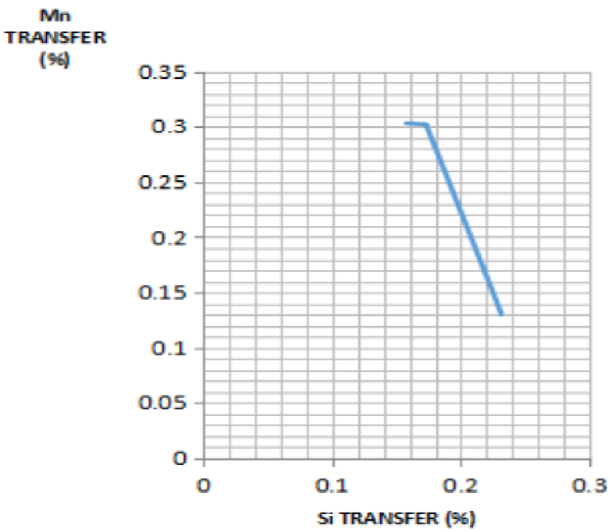


**Figure 2**: Pareto front visualization for case 2: (maximize ($F_{st}$) minimize ($F_{Mn}$))

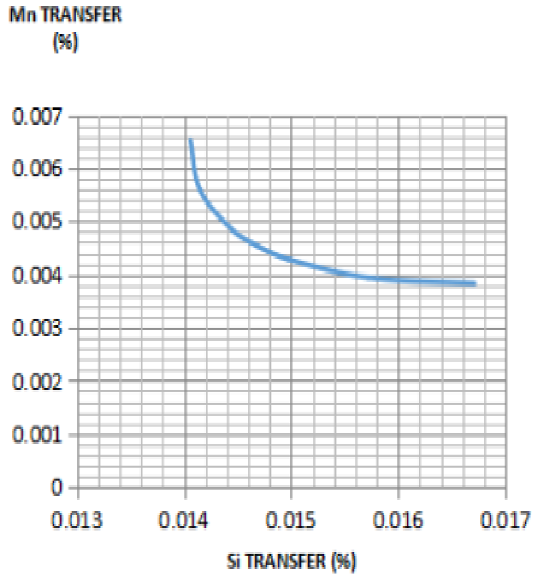


**Figure 3**: Pareto front visualization for case 3: (maximize ($F_{st}$) minimize ($F_{Mn}$))

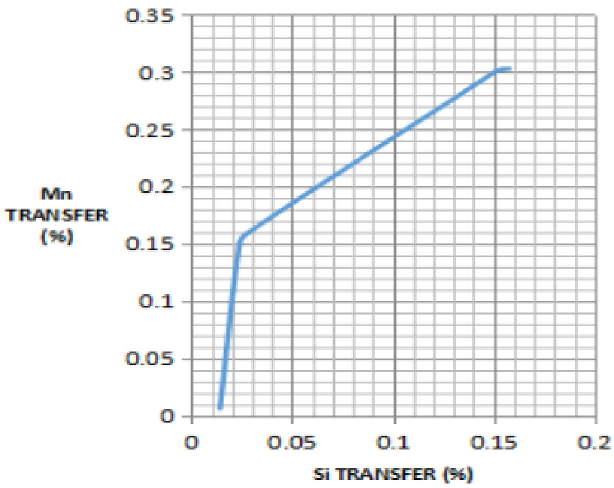


**Figure 4**: Pareto front visualization for case 4: (maximize ($F_{st}$) minimize ($F_{Mn}$)

These boundaries provide the foundation for feasibility evaluation, enabling the identification of unattainable attribute combinations. For example, fluxes B and D were immediately excluded as infeasible because their targets lie outside the feasible domain. Individually, they are insufficient to assess feasibility because the feasible space under them is unbounded. For instance, in Fig. 4 the values for ("ΔSi", "ΔMn"): B (0.07%, 0.26%) and D (0.08%, 0.28%) are not achievable within the present WFD domain because they reside outside the feasible space. Although fluxes A, C, E and F lie within the feasible WFQA space defined by the Pareto front in Fig. 4, it is not immediately clear which ones are attainable. This is because the feasible WFQA space under the Pareto front is unbounded, as a result, it is


https://doi.org/10.4314/njt.2026.5565

not straightforward to determine which fluxes lie within or outside the feasible space. To ascertain their feasibility, the entire feasible WFQA space must be delineated.

The synthesis of Figures 1-4, presented in Figure 5, delineates the boundary of the entire WFQA space and provides a basis for assessing the feasibility of a new flux. As shown in Fig. 5, fluxes B, D, and E are immediately identified as unattainable under the present flux design situation because they lie outside the feasible WFQA space. This implies that no combination of welding flux ingredients can achieve the desired silicon and manganese transfer levels within the flux design domain. This contrasts with past practices, where significant resources were often committed to experimentation before realizing that flux quality attributes were unachievable. Flux E that appeared to lie within the feasible space of Fig. 4 was found to be among the infeasible fluxes when the whole WFQA space was delineated (see Fig. 5). Relying only on one Pareto front for feasibility evaluation may yield misleading results. To develop fluxes B, D, and E, the flux designer must either modify the flux ingredients, the welding wire, or both. Fluxes A, C, and F lie within the feasible WFQA space and are therefore attainable. This framework provides a priori insight on feasibility before embarking on experimentation. Hence, the welding flux designer can initiate the development of fluxes A, C, and F to achieve the desired flux attributes with the existing welding wire.

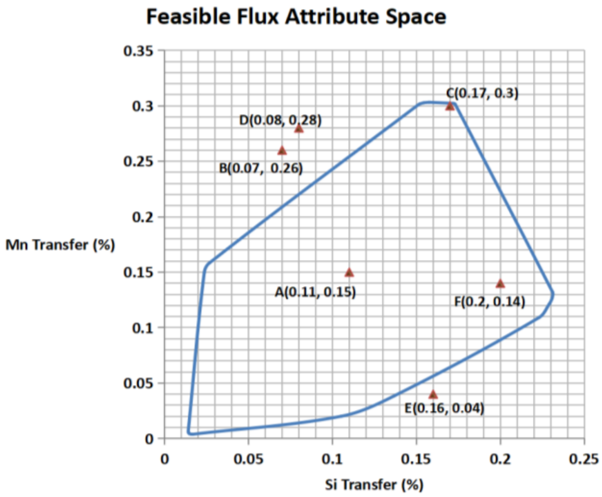


**Figure 5:** Feasible welding flux attribute space

### 4.3 Implications for Resource Management

The implications of using the proposed framework in feasibility assessment are profound. The framework identified fluxes B, D, and E as infeasible prior to conducting any experiment. In the conventional WFD approach, numerous experimental iterations are required to establish the infeasibility of the silicon and manganese transfer levels for these fluxes. By front-loading this knowledge, the systematic framework enables the welding flux formulator to: (1) avoid the expenditure of time, materials, energy, and man-hours on dead-end welding flux development projects; (2) concentrate efforts on attainable and promising flux quality targets; (3) accelerate innovation by eliminating wastes, reduce lead time and produce cost-effective welding fluxes - all of which are critical for aligning the pace of welding flux development with the rapid emergence of new, advanced weldable materials requiring bespoke welding fluxes.

### 4.4 Limitations and future work

The framework presented here is the first attempt to apply a systematic approach to assessing the feasibility of the WFD process. The bi-attribute case used in this study is relatively simple and the feasible attribute space can be represented visually with ease. A systematic approach for establishing the feasibility and visualization of attribute spaces for a higher number of WFQAs is recommended for future studies. The weighted sum approach is a traditional method for successively seeking Pareto-optimal solutions by systematically varying the weight structure of the response functions representing the attributes. This method is suitable for relatively small problems involving convex Pareto fronts. For more complex problems with non-convex regions along the Pareto front, methods such as the ε-constraint, Normal Boundary Intersection and multi-objective evolutionary algorithms such as the NSGA-II algorithm have been used in engineering design optimization. However, their application in WFD has yet to be explored and is therefore recommended for further study.

## 5.0 CONCLUSION

A systematic framework for a priori feasibility evaluation that enables welding flux designers to identify attainable welding flux quality attribute targets before embarking on costly experimentation has been proposed. Through the integration of the response functions, multi-objective optimization and Pareto front analysis, the framework delineates the feasible welding flux quality attributes space. The framework was able to identify achievable and unachievable welding flux quality attributes a priori based on existing flux ingredients and welding wire without any experimentation when applied to bi-attribute design situation. This approach not only conserve resources and compress flux development


https://doi.org/10.4314/njt.2026.5565

time, but also transforms flux design from a process of discovery through costly experimentation into one of front-loading through quantitative insight. This study establishes a systematic framework that embeds feasibility evaluation in the welding flux design. By delineating the feasible attribute space, the framework shifts flux development from costly trial-and-error experimentation to a front-loaded, quantitative design process. Future work should extend the framework to higher-dimensional welding flux quality attributes and explore advanced multi-criteria algorithms to accommodate non-convex Pareto fronts to broaden the applicability of the framework and further align flux development with the rapid evolution of new weldable materials.

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