ON DUALITY THEORY FOR MULTIOBJECTIVE SEMI-INFINITE FRACTIONAL OPTIMIZATION MODEL USING HIGHER ORDER CONVEXITY

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Abstract. In the article, a semi-infinite fractional optimization model having multiple objectives is first formulated. Due to the presence of support functions in each numerator and denominator with constraints, the model so constructed is also non-smooth. Further, three different types of dual models viz Mond-Weir, Wolfe and Schaible are presented and then usual duality results are proved using higher-order \((K \times Q) - (F, \alpha, \rho, d)\)-type I convexity assumptions. To show the existence of such generalized convex functions, a nontrivial example has also been exemplified. Moreover, numerical examples have been illustrated at suitable places to justify various results presented in the paper. The formulation and duality results discussed also generalize the well known results appeared in the literature.

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1. Introduction

A semi-infinite model (SIM) is an optimization problem having finite number of variables with the infinite number of constraints. Initially, in 1962, SIM is named by Charnes et al. [6], in which a survey of SIM mainly about a linear model and duality results with convex property have been done. In this direction, some important theorems for the linear model have been generalized using the pairing of finite space of sequences and vector space of finite dimension. Later, the application of SIM in Euclidean space has been shown by Charnes et al. [7] and its implication in duality results for a \(n\)-dimensional convex minimization problem have been demonstrated. For these convex problems, Karney [18] proposed duality results using its Lagrangian dual. Jeyakumar [14] introduced new constraints qualifications for convex SIM and then developed a strong duality relation. SIM is important for both its results and latent applications in different mathematical fields. It is not only used in the practical problems in which constraints have time or space parameters but also in the areas related to statistics, robotics, transportation problems, game theory and engineering. For more details about significance of SIM, we refer to [11,12,20,23,28,36]. Ito et al. [13] have derived optimality conditions and duality results for the convex SIM using Slater’s constraint qualification. After that, considering constraints over arbitrary cones, Shapiro [27] has developed weak and strong duality relations for convex SIM. Next, Gupta and Srivastava [10] have discussed KKT results for the nonsmooth multiobjective programming problem and then developed usual duality relations. An algorithm based on parametric dual for the quadratic semi-infinite problem have been

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proposed and convergence of the method is shown in Liu et al. [21]. Further, Basu et al. [5] have discussed the duality gap for SIM with the support dual.

Using generalized \((\eta, \rho)\)-invexity, Zalmai and Zhang [37] have developed non-parametric duality relations for semi-infinite discrete minimax fractional problem and further, second-order parameter free duality results are established by Zalmai [36]. After that, Antczak and Zalmai [3] have established second-order relations for semi-infinite minimax type fractional optimization using \((\Phi, \rho) - V\)-invexity assumptions. These invexity conditions are later on extended to higher-order in Stancu-Minasian et al. [30]. Considering the same optimization model [3], Verma and Zalmai [35] have studied a parameter free dual model and established duality results using \((\phi, \rho, \theta, \tilde{m})\)-sonvexity. Later, the approximate duality relations for nonsmooth minimax fractional optimization model using higher order \(B - (p, r)\) invexity have been discussed in Sonali et al. [29].

Mishra and Jaiswal [22] have discussed SIM involving equilibrium constraints and derived optimality conditions with duality results using invexity property. For SIM, considering the concept of convexificators, Pandey and Mishra [24, 25] have proposed necessary as well as sufficient optimality conditions. Further, they formulated Mond-Weir and Wolfe type duals, and proved related theorems with the help of \(\partial^*\)-convexity\ generalized convexity. Slater’s constraints qualification is used for a quasiconvex SIM and then optimality theorems with duality relations are established by Kanzi and Soleimani-damaneh [17]. A fractional semi-infinite problem with \((H_p, R)\)-invexity have been studied in Patel and Patel [26].

Recently, a robust approximation approach is applied in fractional semi-infinite programming and some interesting results for optimality solution with approximation have been established in Zeng et al. [38]. After that, mixed type dual models are formulated and approximate dual relations are discussed for nonlinear SIM in Sun et al. [31, 32]. For a robust vector optimization problem, inspiring from the concept of Quasi \(\epsilon\)-solution for SIM in Jiao et al. [15], necessary and sufficient optimality relations between feasible solution and \(\epsilon\)-solution are developed in Antczak et al. [4]. Using convex decomposition, optimality conditions and extended duality results are developed for generalized SIM by Aboussoror et al. [1]. In Tung [33, 34], subdifferential in terms of tangential convexity is used for developing KKT and strong KKT optimality results for multiobjective SIM. In terms of invexity and equilibrium constraints, sufficient optimality conditions and duality results for two dual models have been derived in Joshi [16]. Recently, Emam [9] has studied a nonsmooth SIM involving \(E\)-convexity and support functions, and further established duality results by constructing Mond-Weir type dual model.

Liang et al. [19] have introduced the concept of generalized \((\mathcal{F}, \alpha, \rho, d)\) convexity and further for fractional optimization model, they have derived optimality relations and usual duality theorems. Using the same type of convexity, higher order dual models are formulated and optimality relations are derived for minimax type problems in Ahmad et al. [2]. Motivated by the work in [2, 19, 34], in this paper, we have studied a new class of semi-infinite fractional programming over arbitrary cones. The main outcomes of the paper are briefly explained below:

- **Problem formulation:** A new class of semi-infinite fractional multiple objective problem over arbitrary cones has been formulated. Due to the presence of support functions in each numerator and denominator of the objective function and in each constraint, the problem becomes non-smooth. This not only generalizes all the existing semi-infinite models but also gives infinitely many optimization problems since it involves arbitrary cones.

- **Assumptions:** The concept of higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, d)\)-type \(I\) convexity is introduced whose existence is further illustrated by citing a non-trivial example.

- **Dual problems:** Three dual models (Wolfe/Mond-Weir/Schaible) have been constructed and appropriate duality relations have been established under the said assumption.

- **Numerical illustrations:** Various non-trivial examples have been exemplified at suitable places to justify the results obtained in the article. Further, it has been shown by giving examples that without satisfying the assumption of higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, d)\)-type \(I\) convexity, the result obtained may not hold.

This paper is organized as: In Section 2, some notations and preliminary results are recalled. Also, the concept of higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, d)\)-type \(I\) convexity is introduced and further, a non-trivial example has
been demonstrated. In Sections 3–5, for a class of a non-smooth multiple objective semi-infinite fractional programming problem, higher order Mond-Weir, Wolfe and Schaible type dual models are constructed, and usual duality results are proved under aforesaid assumption. To validate and clarify the duality results, different numerical examples are also shown at suitable places. In the last section, the conclusion with future scope is given.

2. Preliminaries

Consider the following cone optimization model:

\[
\begin{align*}
\text{(MP)} & \quad K - \min \psi(x) \\
\text{subject to} & \quad -\phi(x) \in Q, \\
& \quad x \in B
\end{align*}
\]

where \(B \subseteq \mathbb{R}^n\) is open and \(\psi : B \to \mathbb{R}^k\), \(\phi : B \to \mathbb{R}^m\) are differentiable vector functions. The set \(K \subseteq \mathbb{R}^k\), \(Q \subseteq \mathbb{R}^m\) are closed convex cones with non-empty interiors and \(K \cap -K = \{0\}\). Let \(B_0 = \{x \in B : -\phi(x) \in Q\}\) denotes the feasible region of the problem (MP).

**Definition 2.1** ([19]). A point \(\tilde{x} \in B_0\) is said to be an efficient (weakly efficient) solution if there exists no \(x \in B_0\) such that \(\psi(\tilde{x}) - \psi(x) \in K \setminus \{0\}(\text{int } K)\).

**Definition 2.2** ([2]). A functional \(F : B \times B \times \mathbb{R}^n \to \mathbb{R}\) is called sublinear in the third component, if for all \((x, u) \in B \times B\),

(i) \(F(x, u; b_1 + b_2) \leq F(x, u; b_1) + F(x, u; b_2)\), for all \(b_1, b_2 \in \mathbb{R}^n\),

(ii) \(F(x, u; \gamma b) = \gamma F(x, u; b)\), for all \(\gamma \in \mathbb{R}^+\) and \(b \in \mathbb{R}^n\).

**Definition 2.3.** Let \(F : B \times B \times \mathbb{R}^n \to \mathbb{R}\) be a sublinear functional in the third variable. Then the pair \((\psi, \phi)\) is called (strictly) higher order \((K \times Q) - (F, \alpha, \rho, d)\)-type \(I\) convex at \(\tilde{u} \in \mathbb{R}^n\) with respect to \(L : B \times \mathbb{R}^n \to \mathbb{R}^k\) and \(S : B \times \mathbb{R}^n \to \mathbb{R}^m\), if for all \(x \in B\), \(p, q \in \mathbb{R}^n\), there exist real valued function \(\alpha(\cdot, \cdot, \cdot) : B \times B \to \mathbb{R}_+ \setminus \{0\}\), a function \(d = (d_i^{(1)}, d_j^{(2)}) : B \times B \to \mathbb{R} \times \mathbb{R}\) and a real number \(\rho = (\rho_i^{(1)}, \rho_j^{(2)}) \in \mathbb{R} \times \mathbb{R}, \ i = 1, 2, \ldots, k, \ j = 1, 2, \ldots, m\), such that

\[
\begin{align*}
&\left(\psi_1(x) - \psi_1(\tilde{u}) - L_1(\tilde{u}, p_1) + p_1^T \nabla p_1 L_1(\tilde{u}, p_1) - F_{x, \tilde{u}} [\alpha(x, \tilde{u}) (\nabla x \psi_1(\tilde{u}) + \nabla p_1 L_1(\tilde{u}, p_1))] \\
&\quad - p_1^{(1)} \left( d_1^{(1)}(x, \tilde{u}) \right)^2 , \ldots , \psi_k(x) - \psi_k(\tilde{u}) - L_k(\tilde{u}, p_k) + p_k^T \nabla p_k L_k(\tilde{u}, p_k) \\
&\quad - F_{x, \tilde{u}} [\alpha(x, \tilde{u}) (\nabla x \psi_k(\tilde{u}) + \nabla p_k L_k(\tilde{u}, p_k))] - \rho_k^{(1)} \left( d_k^{(1)}(x, \tilde{u}) \right)^2 \right) \in K (K \setminus \{0\}) \text{ and}
\end{align*}
\]

\[
\begin{align*}
&\left(- \phi_1(\tilde{u}) - S_1(\tilde{u}, q_1) + q_1^T \nabla q_1 S_1(\tilde{u}, q_1) - F_{x, \tilde{u}} [\alpha(x, \tilde{u}) (\nabla x \phi_1(\tilde{u}) + \nabla q_1 S_1(\tilde{u}, q_1))] \\
&\quad - \rho_i^{(2)} \left( d_i^{(2)}(x, \tilde{u}) \right)^2 , \ldots , - \phi_m(\tilde{u}) - S_m(\tilde{u}, q_m) + q_m^T \nabla q_m S_m(\tilde{u}, q_m) \\
&\quad - F_{x, \tilde{u}} [\alpha(x, \tilde{u}) (\nabla x \phi_m(\tilde{u}) + \nabla q_m S_m(\tilde{u}, q_m))] - \rho_m^{(2)} \left( d_m^{(2)}(x, \tilde{u}) \right)^2 \right) \in Q (Q \setminus \{0\}).
\end{align*}
\]

Next, we will show a non-trivial example to illustrate the existence of such functions.
Example 2.4. In problem (MP), let the functions \( \psi : \mathbb{R} \to \mathbb{R}^2, \phi : \mathbb{R} \to \mathbb{R}^2, L : \mathbb{R} \times \mathbb{R} \to \mathbb{R}^2, S : \mathbb{R} \times \mathbb{R} \to \mathbb{R}^2 \) be given by:

\[
\psi = (\psi_1, \psi_2) = (x^2 + 1, x^2 - 1), \quad \phi = (\phi_1, \phi_2) = (x^2 - 1, x^4 - 1),
\]

\[
L(u, p) = (L_1(u, p_1), L_2(u, p_2)) = (-2p_1u^2, -p_2(u + 1)),
\]

\[
S(u, q) = (S_1(u, q_1), S_2(u, q_2)) = (-q_1u^2 + \frac{5}{2}, -4q_2u^2).
\]

Let \( d_1^{(1)}(x, y) = d_1^{(2)}(x, y) = x - y, \) \( d_2^{(1)}(x, y) = d_2^{(2)}(x, y) = x + y \) and \( \alpha(x, y) = x^2 + 1. \) Let \( F_{x, u}(b) = b(x^2 - u^2), \) \( K = \{(x, y) \in \mathbb{R}^2 : x \leq 0, y \geq x\} \) and \( Q = \{(x, y) \in \mathbb{R}^2 : y \geq 0, y \geq x\}. \) Now, \( -\phi(x) \in Q \) implies \( x^2 \leq 1, \) therefore \(-1 \leq x \leq 1.\) Hence, the feasible region of the problem (MP) is \( B_0 = [-1, 1]\). Next, for all \( x \in \mathbb{R}, p_1, p_2, q_1, q_2 \in \mathbb{R} \) and for \( \rho_1^{(1)} = 1, \rho_2^{(1)} = -1, \) we have

\[
\left\{ \begin{array}{l}
\psi_1(x) - \psi_1(u) - L_1(u, p_1) + p_1^T \nabla_p L_1(u, p_1) - F_{x, u} [\alpha(x, u) (\nabla_x \psi_1(u) + \nabla_p L_1(u, p_1))] \\
- \rho_1^{(1)} \left( d_1^{(1)}(x, u) \right)^2, \quad \psi_2(x) - \psi_2(u) - L_2(u, p_2) + p_2^T \nabla_p L_2(u, p_2)
\end{array} \right. \\
= \left\{ \begin{array}{ll}
(0, 3x^2 + x^4) \in K & \text{at } u = 0, \\
(2x - 2, 2x(x + 1)) \in K \setminus \{0\} & \text{at } u = 1
\end{array} \right.
\]

and also for all \( x \in \mathbb{R}, \rho_1^{(2)} = 1, \rho_2^{(2)} = -1, \) we obtain

\[
\left\{ \begin{array}{l}
- \phi_1(u) - S_1(u, q_1) + q_1^T \nabla_q S_1(u, q_1) - F_{x, u} [\alpha(x, u) (\nabla_x \phi_1(u) + \nabla_q S_1(u, q_1))] \\
- \rho_1^{(2)} \left( d_1^{(2)}(x, u) \right)^2, \quad -\phi_2(u) - S_2(u, q_2) + q_2^T \nabla_q S_2(u, q_2)
\end{array} \right. \\
= \left\{ \begin{array}{ll}
(-x^2 - \frac{3}{2}, 1 + x^2) \in Q & \text{at } u = 0, \\
(-x^4 - x^2 + 2x - \frac{5}{2}, (1 + x)^2) \in Q \setminus \{0\} & \text{at } u = 1.
\end{array} \right.
\]

Hence, the pair \((\psi, \phi)\) is higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, d)\)-type-I convex at \( u = 0 \) and \((\psi, \phi)\) is strictly higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, d)\)-type-I convex at \( u = 1.\)

Definition 2.5 ([31]). Let \( f : \mathbb{R}^n \to \mathbb{R} \) be a convex function. Then, the subdifferential of \( f \) at \( \tilde{x} \) is defined as

\[
\partial f(\tilde{x}) = \{ \tilde{\nu} \in \mathbb{R}^n : f(x) - f(\tilde{x}) \geq \langle \tilde{\nu}, x - \tilde{x} \rangle, \text{for all } x \in \mathbb{R}^n \}.
\]

Definition 2.6 ([8]). The support function of a compact convex set \( A \subseteq \mathbb{R}^n \) is defined as

\[
\Omega(x|A) = \max \{ x^T y : y \in A \}.
\]
The subdifferential of support function $\Omega(x|A)$ at $\bar{x}$ is given by

$$\partial \Omega(\bar{x}|A) = \left\{ \tilde{\nu} \in \mathbb{R}^n : \Omega(\bar{x}|A) = \tilde{\nu}^T \bar{x} \right\}.$$

Now, consider the semi-infinite multiobjective fractional programming problem as follows:

\[
\text{(SIFP) } K - \min \frac{f(x)}{g(x)} = \left( \frac{f_1(x) + \Omega(x|C_1)}{g_1(x) - \Omega(x|D_1)}, \ldots, \frac{f_k(x) + \Omega(x|C_k)}{g_k(x) - \Omega(x|D_k)} \right)
\]

subject to $- [h_j(x, t) + \Omega(x|E_j) + \Omega(t|M_j)] \in Q$, for all $t \in T$

where $i \in \tilde{I} = \{1, 2, \ldots, k\}$, $j \in \tilde{J} = \{1, 2, \ldots, m\}$, $f : \mathbb{R}^n \to \mathbb{R}^k$, $g : \mathbb{R}^n \to \mathbb{R}^k$, $h : \mathbb{R}^n \to \mathbb{R}^m$ are continuously differentiable functions and for compact convex sets $C_i$, $D_i$, $E_j$ and $M_j$ in $\mathbb{R}^n$, respective support functions are $\Omega(x|C_i)$, $\Omega(x|D_i)$, $\Omega(x|E_j)$ and $\Omega(x|M_j)$ for $i \in \tilde{I}$, $j \in \tilde{J}$. Also, assume that $f_i(\cdot) + \Omega(\cdot|C_i) \geq 0$ and $g_i(\cdot) - \Omega(\cdot|D_i) > 0$ for all feasible $x$ and $T$ is an infinite index set.

Suppose $S_0 = \{x \in \mathbb{R}^n : - [h_j(x, t) + \Omega(x|E_j) + \Omega(t|M_j)] \in Q$, for all $t \in T\}$ represents the feasible region of the problem (SIFP). Let $K^*$ and $Q^*$ be positive dual cones of $K$ and $Q$, respectively.

Following the lines of Debnath and Gupta [8], we now state the following necessary Karush–Kuhn–Tucker condition for (SIFP):

**Theorem 2.7.** Let $\bar{x} \in B \subseteq \mathbb{R}^n$ be a weakly efficient point of (SIFP) and a suitable constraint qualification be fulfilled at $\bar{x}$. Then, there exist $(\lambda, \mu) \in \text{int } K^* \times \text{int } Q^*$, $(\lambda, \mu) \neq (0, 0)$ and $t \in T$ such that

\[
0 \in \partial \left( \sum_{i=1}^k \lambda_i \left( f_i(\bar{x}) + \Omega(\bar{x}|C_i) \right) g_i(\bar{x}) - \Omega(\bar{x}|D_i) \right) + \sum_{j=1}^m \mu_j \left( h(\bar{x}, t) + \Omega(\bar{x}|E_j) + \Omega(t|M_j) \right)
\]

\[
\sum_{j=1}^m \mu_j (h(\bar{x}, t) + \Omega(\bar{x}|E_j) + \Omega(t|M_j)) = 0.
\]

3. Mond-Weir Type Dual

For (SIFP) model, consider the following Mond-Weir type higher order dual:

\[
\text{(MD) } K - \max \left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1}, \ldots, \frac{f_k(u) + u^T z_k}{g_k(u) - u^T v_k} \right)
\]

subject to

\[
\sum_{i=1}^k \lambda_i \left[ \nabla_x \left( \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right) + \nabla_{p_i} L_i(u, p_i) \right]
\]

\[
+ \sum_{j=1}^m \mu_j \left[ \nabla_x (h_j(u, \tau) + u^T w^1_j + \tau^T w^2_j) + \nabla_{q_j} S_j(u, q_j) \right] = 0,
\]

\[
\sum_{j=1}^m \nu_j \left[ h_j(u, \tau) + u^T w^1_j + \tau^T w^2_j + S_j(u, q_j) - q_j^T \nabla_{q_j} S_j(u, q_j) \right] \geq 0,
\]

\[
\sum_{i=1}^k \lambda_i [L_i(u, p_i) - p_i^T \nabla_{p_i} L_i(u, p_i)] \geq 0,
\]

$z_i \in C_i$, $v_i \in D_i$, $w^1_j \in E_j$, $w^2_j \in M_j$, $i \in \tilde{I}$, $j \in \tilde{J}$, $(\lambda, \mu) \in \text{int } K^* \times \text{int } Q^*$, $(\lambda, \mu) \neq (0, 0)$ and $\tau \in T$. 
Theorem 3.1 (Weak duality). Assume that \( x \) and \((u, v, w^1, w^2, \lambda, \mu, z, p, q)\) be feasible for the problems (SIFP) and (MD), respectively. Let a sublinear functional (in third variable) be \( F : B \times B \times \mathbb{R}^n \to \mathbb{R} \). Let \( \mathbf{(i)} \) (Weak duality) \( (h_1(\cdot, \tau) + (\cdot)^T w^1, \ldots, h_m(\cdot, \tau) + (\cdot)^T w^1_m) \) be higher order \((K \times Q) \) - \((F, \alpha, \rho, d)\)-type \( I \) convex at \( u \) with respect to \( L \) and \( S \),

\[
\sum_{k=1}^k \lambda_i f_i(x) + x^T z_i \geq \sum_{j=1}^m \mu_j \left( \rho_j^2 \left( d_j^m(x, u) \right)^2 - \tau^T w_j^2 \right) \geq 0.
\]

Then

\[
\begin{align*}
(f_1(u) + u^T z_1, \ldots, f_k(u) + u^T z_k) - (f_1(x) + \Omega(x|C_1), \ldots, f_k(x) + \Omega(x|C_k)) \notin K \setminus \{0\}. \tag{3.4}
\end{align*}
\]

Proof. By hypothesis (i) and Definition 2.3 at \( u \) with respect to \( L : B \times \mathbb{R}^n \to \mathbb{R}^k \) and \( S : B \times \mathbb{R}^n \to \mathbb{R}^m \), we have

\[
\begin{align*}
&\left( f_1(x) + x^T z_1 \right) - \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} - L_1(u, p_1) + p_1^T \nabla_p L_1(u, p_1) - \mathcal{F}_{x,u} \left[ \alpha(x, u) \left( \nabla_x \left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} \right) \right) \right] \\
&- \nabla_x \left( f_1(x) + \Omega(x|C_1) \right) + \nabla_x \left( \nabla_x \left( f_1(u) + u^T z_1 \right) \right) + \nabla_x \left( \nabla_x \left( \Omega(x|C_1) \right) \right) - \rho_1^2 \left( d_1^m(x, u) \right)^2 \in K \tag{3.5}
\end{align*}
\]

and

\[
\begin{align*}
&\left( -h_1(u, \tau) + u^T w^1 \right) - S_1(u, q_1) + q_1^T \nabla_q S_1(u, q_1) - \mathcal{F}_{x,u} \left[ \alpha(x, u) \left( \nabla_x \left( h_1(u, \tau) + u^T w^1 \right) \right) \right] \\
&+ \nabla_q S_1(u, q_1) \right) - \rho_1^2 \left( d_1^m(x, u) \right)^2 \right) \in Q. \tag{3.6}
\end{align*}
\]

It follows from \( \lambda \in \text{int } K^* \) and (3.5) that

\[
\sum_{i=1}^k \lambda_i \left[ f_i(x) + x^T z_i \right] - \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} - L_i(u, p_i) + p_i^T \nabla_p L_i(u, p_i) - \mathcal{F}_{x,u} \left[ \alpha(x, u) \left( \nabla_x \left( f_i(u) + u^T z_i \right) \right) + \nabla_p L_i(u, p_i) \right] \right] \geq \rho_i^2 \left( d_i^m(x, u) \right)^2 \geq 0.
\]

Using the sublinearity property of \( \mathcal{F} \), \( \lambda \in \text{int } K^* \subseteq \text{int } \mathbb{R}^k_+ \) and dual constraint (3.3), we get

\[
\sum_{i=1}^k \lambda_i \left[ f_i(x) + x^T z_i - \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right] \right] \geq \mathcal{F}_{x,u} \left[ \alpha(x, u) \sum_{i=1}^k \lambda_i \left( \nabla_x \left( \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right) + \nabla_p L_i(u, p_i) \right) \right] + \sum_{i=1}^k \lambda_i \rho_i^2 \left( d_i^m(x, u) \right)^2. \tag{3.7}
\]
Now, from hypothesis (ii), $\mu \in \text{int } Q^* \subseteq \text{int } \mathbb{R}^m_+$, it follows from (3.6) that
\[
\sum_{j=1}^{m} \mu_j \left[ -(h_j(u, \tau) + u^T w_j^0) - S_j(u, q_j) + q_j^T \nabla q_j S_j(u, q_j) \right. \\
- \mathcal{F}_{x,u} \left\{ \alpha(x, u) \left( \nabla_x (h_j(u, \tau) + u^T w_j^0) + \nabla q_j S_j(u, q_j) \right) \right\} - \rho_j^{(2)} \left( d_j^{(2)}(x,u) \right)^2 \right] \geq 0.
\]

Using $\mu > 0$, along with sublinearity of $\mathcal{F}$, the above inequality gives
\[
\sum_{j=1}^{m} \mu_j \left[ -(h_j(u, \tau) + u^T w_j^0) - S_j(u, q_j) + q_j^T \nabla q_j S_j(u, q_j) \right. \\
\left. \geq \mathcal{F}_{x,u} \left\{ \alpha(x, u) \sum_{j=1}^{m} \mu_j \left\{ \nabla_x (h_j(u, \tau) + u^T w_j) + \nabla q_j S_j(u, q_j) \right\} \right\} + \sum_{j=1}^{m} \mu_j \rho_j^{(2)} \left( d_j^{(2)}(x,u) \right)^2. \quad (3.8)\right.
\]

Further, using inequality (3.2) in the addition of (3.7) and (3.8), we obtain
\[
\sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} - \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right] \\
\geq \mathcal{F}_{x,u} \left\{ \alpha(x, u) \sum_{i=1}^{k} \lambda_i \left\{ \nabla_x \left( \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right) + \nabla p_i \left( \Omega(x, C_i) \right) \right\} \right\} + \mathcal{F}_{x,u} \left\{ \alpha(x, u) \sum_{j=1}^{m} \mu_j \left\{ \nabla_x (h_j(u, \tau) + u^T w_j) + \nabla q_j S_j(u, q_j) \right\} \right\} + \sum_{i=1}^{k} \lambda_i \rho_i^{(1)} \left( d_i^{(1)}(x,u) \right)^2 + \sum_{j=1}^{m} \mu_j \rho_j^{(2)} \left( d_j^{(2)}(x,u) \right)^2 - \tau^T w_j^2. \quad (3.9)\right.
\]

It follows from assumption (iii), dual constraint (3.1), sublinearity of $\mathcal{F}$ and $\mathcal{F}_{x,u}(0) = 0$ that
\[
\sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} - \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right] \geq 0. \quad (3.9)\right.
\]

Now, on the contrary, suppose that (3.4) is not correct. Then, $\lambda \in \text{int } K^*$ implies
\[
\sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} - \frac{f_i(x) + \Omega(x|C_i)}{g_i(x) - \Omega(x|D_i)} \right] > 0.
\]

Finally, since $x^T z_i \leq \Omega(x|C_i), x^T v_i \leq \Omega(x|D_i)$ and $\lambda_i > 0$, for all $i$, therefore
\[
\sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} - \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} \right] > 0
\]

which contradicts the inequality (3.9). This completes the proof. \hfill \Box

**Theorem 3.2 (Strong duality).** Let $\hat{x} \in B$ be a weakly efficient solution of (SIFP) and the suitable constraint qualification holds at $\hat{x}$. Then, for $L_i(\hat{x}, 0) = 0, S_j(\hat{x}, 0) = 0, \nabla \hat{p}, L_i(\hat{x}, 0) = 0$ and $\nabla \hat{q}, S_j(\hat{x}, 0) = 0, i \in \tilde{I}, j \in \tilde{J}$, there exist $\hat{\lambda} = (\hat{\lambda}_1, \ldots, \hat{\lambda}_k) \in \text{int } K^*, \hat{\mu} = (\hat{\mu}_1, \ldots, \hat{\mu}_m) \in \text{int } Q^*$, with $(\hat{\lambda}, \hat{\mu}) \neq (0, 0)$ such that $(\hat{x}, \hat{v}, \hat{w}^1, \hat{w}^2, \hat{\lambda}, \hat{\mu}, \hat{z}, \hat{p}, \hat{q}) = 0$ is a feasible point of (MD) and the objective function values of (SIFP) and (MD) are equal. Moreover, if all the assumptions of Theorem 3.1 are satisfied for every feasible point $\hat{x}$ of (SIFP) and $(\hat{u}, \hat{v}, \hat{w}^1, \hat{w}^2, \hat{\lambda}, \hat{\mu}, \hat{z}, \hat{p}, \hat{q})$ of (MD), then $(\hat{x}, \hat{v}, \hat{w}^1, \hat{w}^2, \hat{\lambda}, \hat{\mu}, \hat{z}, \hat{p}, \hat{q}) = 0$ is an efficient solution of (MD).
Theorem 3.3

Proof. For the weakly efficient solution \( \tilde{x} \in S_0 \) of (SIFP), from Theorem 2.7, there exist \( \tilde{\lambda}, \tilde{\mu} \in \text{int } Q^* \), \( (\tilde{\lambda}, \tilde{\mu}) \neq (0, 0) \) and \( \tilde{t} \in T \) such that

\[
0 \in \partial \left( \sum_{i=1}^{k} \lambda_i \left( \frac{f_i(\tilde{x}) + \Omega(\tilde{x}|C_i)}{g_i(\tilde{x}) - \Omega(\tilde{x}|D_i)} \right) \right) + \sum_{j=1}^{m} \mu_j \left( h_j(\tilde{x}, \tilde{t}) + \Omega(\tilde{x}|E_j) + \Omega(\tilde{t}|M_j) \right)
\]

and

\[
\sum_{j=1}^{m} \mu_j \left( h(\tilde{x}, \tilde{t}) + \Omega(\tilde{x}|E_j) + \Omega(\tilde{t}|M_j) \right) = 0
\]

which implies

\[
0 \in \left( \sum_{i=1}^{k} \lambda_i \partial \left( \frac{f_i(\tilde{x}) + \Omega(\tilde{x}|C_i)}{g_i(\tilde{x}) - \Omega(\tilde{x}|D_i)} \right) \right) + \sum_{j=1}^{m} \mu_j \partial \left( h_j(\tilde{x}, \tilde{t}) + \Omega(\tilde{x}|E_j) + \Omega(\tilde{t}|M_j) \right)
\].

For \( \tilde{z} \in \partial \Omega(\tilde{x}|C_i), \tilde{v} \in \partial \Omega(\tilde{x}|D_i), \tilde{w}^1, \tilde{w}^2 \in \partial \Omega(\tilde{x}|E_j) \) and \( \tilde{w}^2_2 \in \partial \Omega(\tilde{t}|M_j) \), we have

\[\Omega(\tilde{x}|C_i) = \tilde{x}^T \tilde{z}, \Omega(\tilde{x}|D_i) = \tilde{x}^T \tilde{v}, \Omega(\tilde{x}|E_j) = \tilde{x}^T \tilde{w}^1 \text{ and } \Omega(\tilde{t}|M_j) = \tilde{t}^T \tilde{w}^2_2.\]

It further follows that

\[
\sum_{i=1}^{k} \lambda_i \nabla \left( \frac{f_i(\tilde{x}) + \tilde{x}^T \tilde{z}_1}{g_i(\tilde{x}) - \tilde{x}^T \tilde{v}_1} \right) + \sum_{j=1}^{m} \mu_j \nabla \left( h_j(\tilde{x}, \tilde{t}) + \tilde{x}^T \tilde{w}^1_j + \tilde{t}^T \tilde{w}^2_j \right) = 0
\]

and

\[
\sum_{j=1}^{m} \mu_j \left( h(\tilde{x}, \tilde{t}) + \tilde{x}^T \tilde{w}^1_j + \tilde{t}^T \tilde{w}^2_j \right) = 0.
\]

The above equations with \( L_i(\tilde{u}, 0) = 0, S_i(\tilde{x}, 0) = 0, \nabla \tilde{p}_i L_i(\tilde{x}, 0) = 0, \nabla \tilde{q}_j S_j(\tilde{x}, 0) = 0 \) imply that \( (\tilde{x}, \tilde{v}, \tilde{w}^1, \tilde{w}^2, \tilde{\lambda}, \tilde{\mu}, \tilde{z}, \tilde{p} = 0, \tilde{q} = 0) \) is feasible for (MD) and respective values of objective functions are equal.

Now, suppose that \( (\tilde{x}, \tilde{v}, \tilde{w}^1, \tilde{w}^2, \tilde{\lambda}, \tilde{\mu}, \tilde{z}, \tilde{p} = 0, \tilde{q} = 0) \) is not an efficient solution of (MD), then there exists a feasible point \( (u, v, w^1, w^2, \lambda, \mu, p, q) \) of (MD) such that

\[
\left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1}, \ldots, \frac{f_k(u) + u^T z_k}{g_k(u) - u^T v_k} \right) - \left( \frac{f_1(\tilde{x}) + \tilde{x}^T \tilde{z}_1}{g_1(\tilde{x}) - \tilde{x}^T \tilde{v}_1}, \ldots, \frac{f_k(\tilde{x}) + \tilde{x}^T \tilde{z}_k}{g_k(\tilde{x}) - \tilde{x}^T \tilde{v}_k} \right) \in K \setminus \{0\}
\]

This further gives

\[
\left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1}, \ldots, \frac{f_k(u) + u^T z_k}{g_k(u) - u^T v_k} \right) - \left( \frac{f_1(\tilde{x}) + \Omega(\tilde{x}|C_1)}{g_1(\tilde{x}) - \Omega(\tilde{x}|D_1)}, \ldots, \frac{f_k(\tilde{x}) + \Omega(\tilde{x}|C_k)}{g_k(\tilde{x}) - \Omega(\tilde{x}|D_k)} \right) \in K \setminus \{0\}
\]

which contradicts Theorem 3.1. Hence proved. □

Theorem 3.3 (Strict converse duality). Let \( \tilde{x} \) and \( (\tilde{u}, \tilde{v}, \tilde{w}^1, \tilde{w}^2, \tilde{\lambda}, \tilde{\mu}, \tilde{z}, \tilde{p}, \tilde{q}) \) be feasible solutions of the problems (SIFP) and (MD), respectively. Let a sublinear functional (in third variable) be \( F: B \times B \times \mathbb{R}^n \rightarrow \mathbb{R} \) such that

\[
(i) \left( \frac{f_1(\tilde{u}) + \tilde{u}^T \tilde{z}_1}{g_1(\tilde{u}) - \tilde{u}^T \tilde{v}_1} - \sum_{j=1}^{m} \mu_j \{ h_j(\tilde{u}, \tilde{\tau}) + \tilde{u}^T \tilde{w}^1_j + \tilde{\tau}^T \tilde{w}^2_j + S_j(\tilde{u}, \tilde{q}_j) \} - \tilde{q}_j^T \nabla \tilde{q}_j S_j(\tilde{u}, \tilde{q}_j) \right) - \left( \frac{f_1(\tilde{\tau}) + \tilde{\tau}^T \tilde{z}_1}{g_1(\tilde{\tau}) - \tilde{\tau}^T \tilde{v}_1} - \sum_{j=1}^{m} \mu_j \{ h_j(\tilde{\tau}, \tilde{\tau}) + \tilde{\tau}^T \tilde{w}^1_j + \tilde{\tau}^T \tilde{w}^2_j + S_j(\tilde{\tau}, \tilde{q}_j) \} - \tilde{q}_j^T \nabla \tilde{q}_j S_j(\tilde{\tau}, \tilde{q}_j) \right) \in K,
\]
Further, using (3.1) and hypothesis (iv), we obtain

\[
\left( f_1(\cdot) + (\cdot)^T z_1 \\
g_1(\cdot) - (\cdot)^T v_1 \\
\vdots \\
f_k(\cdot) + (\cdot)^T z_k \\
g_k(\cdot) - (\cdot)^T v_k \right), \quad (h_1(\cdot, \tau) + (\cdot)^T w_1, \ldots, h_m(\cdot, \tau) + (\cdot)^T w_m) \]

be strictly higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, d)\)-type I convex at \(\tilde{u}\) with respect to \(L\) and \(S\),

so that \(K \supseteq \mathbb{R}^k_+\), \(Q \supseteq \mathbb{R}^m_+\) and

\[
\sum_{i=1}^k \bar{\lambda}_i \rho_i^{(1)} \left( d_i^{(1)}(\tilde{x}, \tilde{u}) \right)^2 + \sum_{j=1}^m \bar{\mu}_j \rho_j^{(2)} \left( d_j^{(2)}(\tilde{x}, \tilde{u}) \right)^2 - \tilde{\tau}^T \tilde{w}_j^2 \geq 0.
\]

Then \(\tilde{x} = \tilde{u}\).

**Proof.** Let \(\tilde{x}\) and \((\tilde{u}, \tilde{v}, \tilde{w}^1, \tilde{\lambda}, \tilde{\mu}, \tilde{z}, \tilde{p}, \tilde{q})\) be feasible solutions of the problems (SIFP) and (MD), respectively. On the contrary, suppose that \(\tilde{x} \neq \tilde{u}\). Then, by \(\bar{\lambda} \in \text{int} \ K^* \subseteq \text{int} \ \mathbb{R}^k_+\), and \(\bar{\mu} \in \text{int} \ Q^* \subseteq \text{int} \ \mathbb{R}^m_+\), hypothesis (ii) and Definition 2.3, we obtain

\[
\sum_{i=1}^k \bar{\lambda}_i \left[ \frac{f_i(\tilde{x}) + \tilde{x}^T \tilde{z}_i}{g_i(\tilde{x}) - \tilde{x}^T \tilde{v}_i} - \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} - L_i(\tilde{u}, \tilde{p}_i) + \tilde{p}_i^T \nabla_{\tilde{p}_i} L_i(\tilde{u}, \tilde{p}_i) \right] - \mathcal{F}_{\tilde{x}, \tilde{u}} \left( \left\{ \nabla_{\tilde{z}_i} \left( \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} \right) + \nabla_{\tilde{p}_i} L_i(\tilde{u}, \tilde{p}_i) \right\} \right) > 0. \tag{3.10}
\]

\[
\sum_{j=1}^m \bar{\mu}_j \left( - (h_j(\tilde{u}, \tilde{\tau}) + \tilde{\tau}^T \tilde{w}_j^1) - S_j(\tilde{u}, \tilde{q}_j) + \tilde{q}_j^T \nabla_{\tilde{q}_j} S_j(\tilde{u}, \tilde{q}_j) \right) - \mathcal{F}_{\tilde{x}, \tilde{u}} \left( \left\{ \nabla_{\tilde{z}_i} \left( \frac{h_j(\tilde{u}, \tilde{\tau}) + \tilde{\tau}^T \tilde{w}_j^1}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} \right) + \nabla_{\tilde{q}_j} S_j(\tilde{u}, \tilde{q}_j) \right\} \right) > 0. \tag{3.11}
\]

Further, using the sublinearity of \(\mathcal{F}\) and inequality (3.3) in (3.10), we get

\[
\sum_{i=1}^k \bar{\lambda}_i \left[ \frac{f_i(\tilde{x}) + \tilde{x}^T \tilde{z}_i}{g_i(\tilde{x}) - \tilde{x}^T \tilde{v}_i} - \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} \right] > \mathcal{F}_{\tilde{x}, \tilde{u}} \left( \left\{ \nabla_{\tilde{z}_i} \left( \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} \right) + \nabla_{\tilde{p}_i} L_i(\tilde{u}, \tilde{p}_i) \right\} \right) + \sum_{i=1}^k \bar{\lambda}_i \rho_i^{(1)} \left( d_i^{(1)}(\tilde{x}, \tilde{u}) \right)^2. \tag{3.12}
\]

It follows from (3.2), (3.11), (3.12) and sublinearity of \(\mathcal{F}\) that

\[
\sum_{i=1}^k \bar{\lambda}_i \left[ \frac{f_i(\tilde{x}) + \tilde{x}^T \tilde{z}_i}{g_i(\tilde{x}) - \tilde{x}^T \tilde{v}_i} - \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} \right] > \mathcal{F}_{\tilde{x}, \tilde{u}} \left( \left\{ \nabla_{\tilde{z}_i} \left( \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} \right) + \nabla_{\tilde{p}_i} L_i(\tilde{u}, \tilde{p}_i) \right\} \right) + \sum_{j=1}^m \bar{\mu}_j \left\{ \nabla_{\tilde{z}_i} \left( h_j(\tilde{u}, \tilde{\tau}) + \tilde{\tau}^T \tilde{w}_j^1 \right) + \nabla_{\tilde{q}_j} S_j(\tilde{u}, \tilde{q}_j) \right\} \right) + \sum_{i=1}^k \bar{\lambda}_i \rho_i^{(1)} \left( d_i^{(1)}(\tilde{x}, \tilde{u}) \right)^2 + \sum_{j=1}^m \bar{\mu}_j \rho_j^{(2)} \left( d_j^{(2)}(\tilde{x}, \tilde{u}) \right)^2 - \tilde{\tau}^T \tilde{w}_j^2 \right). \]

Further, using (3.1) and hypothesis (iv), we obtain

\[
\sum_{i=1}^k \bar{\lambda}_i \left[ \frac{f_i(\tilde{x}) + \tilde{x}^T \tilde{z}_i}{g_i(\tilde{x}) - \tilde{x}^T \tilde{v}_i} - \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} \right] > 0. \tag{3.13}
\]
Now, using dual constraint (3.2) and \( \lambda_i \in \text{int } K^* \) in hypothesis (i), we get

\[
\sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(\bar{x}) + \bar{x}^T \bar{z}_i}{g_i(\bar{x}) - \bar{x}^T \bar{v}_i} - \frac{f_i(\bar{u}) + \bar{u}^T \bar{z}_i}{g_i(\bar{u}) - \bar{u}^T \bar{v}_i} \right] \leq 0.
\]

This contradicts the inequality (3.13). Hence the result. \( \square \)

**Example 3.4.** Let in the problem (SIFP), \( f : \mathbb{R} \to \mathbb{R}^2, \ g : \mathbb{R} \to \mathbb{R}^2 \) and \( h : \mathbb{R} \times [-1, 0] \to \mathbb{R}^2 \) be given as:

\[
\begin{align*}
    f(x) &= (f_1(x), f_2(x)) = (x^2 + 2, x^2(x^2 + 1)), \\
    g(x) &= (g_1(x), g_2(x)) = (x^4 + 4, (x^2 + 1)^2) \quad \text{and} \\
    h(x, t) &= (h_1(x), h_2(x, t)) = (x^3t - 2, x^2t).
\end{align*}
\]

Let the cones be \( K = \{(x, y) \in \mathbb{R}^2 : x \geq 0, y \geq -17x\} \) and \( Q = \{(x, y) \in \mathbb{R}^2 : y \geq 0, 2y \geq -x\} \). Also, suppose

\[
\begin{align*}
    L(u, p) &= (L_1(u, p_1), L_2(u, p_2)) = (p_1u, -p_2u), \\
    S(u, q) &= (S_1(u, q_1), S_2(u, q_2)) = (q_1u^2, q_2(u - 1)) \quad \text{and} \\
    d_1^{(1)}(x, y) &= d_1^{(2)}(x, y) = 1 - xy, \quad d_2^{(1)}(x, y) = d_2^{(2)}(x, y) = y^2 + 1.
\end{align*}
\]

Let the sublinear functional be \( F_{x,u}(b) = bxu \) and \( \alpha(x, y) = 1 + x^2y^2 \). Let

\[
C_1 = \{0\}, \quad C_2 = [0, 1] = D_1 = E_2 = M_2, \quad \text{and} \quad D_2 = [-1, 0] = E_1 = M_1.
\]

Thus, their support functions will be

\[
\begin{align*}
    \Omega(x|C_1) &= \{0\}, \quad \Omega(x|D_2) = \Omega(x|E_1) = \frac{|x| - x}{2}, \quad \Omega(t|M_1) = \frac{|t| - t}{2}, \\
    \Omega(x|C_2) &= \Omega(x|D_1) = \Omega(x|E_2) = \frac{x + |x|}{2} \quad \text{and} \quad \Omega(t|M_2) = \frac{|t| + t}{2}.
\end{align*}
\]

The feasible region \( S_0 = \left\{ x \in \mathbb{R} : \left(2 - xt - \frac{|x| - x}{2} - \frac{|t| - t}{2}, -x^2t - \frac{x + |x|}{2} - \frac{|t| + t}{2}\right) \in Q, \right\} \)

for all \( t \in [-1, 0] \).

Clearly, 0, -1 \in \( S_0 \). Also, \( \beta = (u, v, w^1, w^2, \lambda, \mu, z, p, q) = \left(0, (0, 0), (0, 1), (-1, 1), \left(\frac{1}{8}, 2\right), (1, 1), (0, 0), (1, 0), (0, 1)\right) \) is feasible for (MD).

**Validation of Theorem 3.1:**

First we will show that all the hypothesis of Theorem 3.1 are satisfied.
At $u = 0$, for $v = (0, 0)$, $z = (0, 0)$, $\rho_1^{(1)} = -2$ and $\rho_2^{(1)} = \frac{1}{8}$, we get
\[
\left( \begin{array}{c}
\frac{f_1(x) + x^T z_1}{g_1(x) - x^T v_1} - \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} - L_1(u, p_1) + p_1^T \nabla_p L_1(u, p_1) - \mathcal{F}_{x,u} \left[ \alpha(x,u) \left( \nabla_x \left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} \right) \right) \right] \\
\frac{f_2(x) + x^T z_2}{g_2(x) - x^T v_2} - \frac{f_2(u) + u^T z_2}{g_2(u) - u^T v_2} - L_2(u, p_2) + p_2^T \nabla_p L_2(u, p_2) - \mathcal{F}_{x,u} \left[ \alpha(x,u) \left( \nabla_x \left( \frac{f_2(u) + u^T z_2}{g_2(u) - u^T v_2} \right) \right) \right]
\end{array} \right) = (0, 0) \in K \setminus \{0\}, \text{ for all } x \in \mathbb{R}.
\]

Further, for $w^1_1 \in E_1$, $w^1_2 \in E_2$, $w^2_1 \in M_1$, $w^2_2 \in M_2$, $\rho_1^{(2)} = 1$, $\rho_2^{(2)} = -1$ and for all $\tau \in [-1,0]$, we obtain
\[
\left( 1, 1 \right) \in Q \setminus \{0\}.
\]

Hence, the hypothesis (i) of Theorem 3.1 is satisfied. Moreover, $\mathbb{R}^2_+ \subset K$, $\mathbb{R}^2_+ \subset Q$ and
\[
\sum_{i=1}^{2} \lambda_i \rho_i^{(1)} \left( d_i^{(1)}(x,u) \right)^2 + \sum_{j=1}^{2} \mu_j \left( \rho_j^{(2)} \left( d_j^{(2)}(x,u) \right)^2 - \tau T w_j^2 \right) = 0.
\]

Thus, hypotheses (ii) and (iii) of Theorem 3.1 also hold. Now, for $\beta$, the expression
\[
\left( \begin{array}{c}
\frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} - \frac{f_1(x) + \Omega(x|C_1)}{g_1(x) - \Omega(x|D_1)} \\
\frac{f_2(u) + u^T z_2}{g_2(u) - u^T v_2} - \frac{f_2(x) + \Omega(x|C_2)}{g_2(x) - \Omega(x|D_2)}
\end{array} \right) = \begin{cases} 
(0, 0) \notin K \setminus \{0\} & \text{for } x = 0, \\
\left( -\frac{1}{10}, -\frac{2}{3} \right) \notin K \setminus \{0\} & \text{for } x = -1.
\end{cases}
\]

Hence, the Theorem 3.1 is verified at $x = 0$, $-1 \in S_0$ and the point $\beta$ feasible for (MD).

**Validation of Theorem 3.3:**

For the points $\beta$ and $x = 0$, it has been shown above that the assumptions (ii), (iii) and (iv) of Theorem 3.3 hold true. Also, the value of the expression
\[
\begin{align*}
&\left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} - \frac{1}{2} \sum_{j=1}^{2} \mu_j \{ h_j(u,\tau) + u^T w_j^1 + \tau w_j^2 + S_j(u,q_j) - q_j^T \nabla q_j S_j(u,q_j) \} \right) + \frac{f_2(u) + u^T z_2}{g_2(u) - u^T v_2} \\
&- \frac{1}{2} \sum_{j=1}^{2} \mu_j \{ h_j(u,\tau) + u^T w_j^1 + \tau w_j^2 + S_j(u,q_j) - q_j^T \nabla q_j S_j(u,q_j) \}
\end{align*}
\]
\[
= (0, 0) \in K.
\]

Thus, the assumption (i) of Theorem 3.3 also holds. Hence verified.
Hence, the result of Theorem 3.1 does not hold.

Thus, hypotheses (ii) and (iii) of Theorem 3.1 are satisfied but $H(x, t) = (h_1(x, t), h_2(x, t)) = (-x^3 + t + 2, -x^2 t^2).$

Let the cones be $K = \{(x, y) \in \mathbb{R}^2 : x \geq 0, y \geq -2x\}$ and $Q = \{(x, y) \in \mathbb{R}^2 : x \geq 0, y \geq 0\}.$ Also, suppose

\[ L(u, p) = (L_1(u, p_1), L_2(u, p_2)) = (-p_1 u, p_2 u), \]

\[ S(u, q) = (S_1(u, q_1), S_2(u, q_2)) = (q_1 u, q_2 u + 4) \] and

\[ d_1^{(1)}(x, y) = d_1^{(2)}(x, y) = y(x + 1), \quad d_2^{(1)}(x, y) = d_2^{(2)}(x, y) = x^2 y^2. \]

Let the sublinear functional be $F_{x,u}(b) = b^2 xu$ and $\alpha(x, y) = 2 + x^2 y^2.$ Consider

\[ C_1 = \{0\}, \quad C_2 = [-1, 0] = E_1 = M_2 \text{ and } D_1 = D_2 = [0, 1] = E_2 = M_1. \]

Thus, their support functions will be

\[
\Omega(x|C_1) = \{0\}, \quad \Omega(x|C_2) = \Omega(x|E_1) = \frac{|x| - x}{2}, \quad \Omega(t|M_1) = \frac{|t| + t}{2},
\]

\[
\Omega(x|D_1) = \Omega(x|D_2) = \Omega(x|E_2) = \frac{x + |x|}{2} \quad \text{and} \quad \Omega(t|M_2) = \frac{|t| - t}{2}.
\]

One can easily verify that $x = 1$ is feasible for (SIFP) and $\beta_1 = \left(\frac{1}{2}, -1\right), \left(\frac{1}{2}, 1\right), \left(0, 0\right), \left(0, 0\right), \left(0, 2\right), \left(0, 2\right) \right)$ is feasible for (MD). At $\beta_1$, for any $\rho_1^{(1)}, \rho_2^{(1)}, \rho_1^{(2)}, \rho_2^{(2)} \in \mathbb{R},$ since $\mathbb{R}^2_{+} \subset K, \mathbb{R}^2_{+} \subset Q$ and

\[
\sum_{i=1}^{2} \lambda_i \rho_i^{(1)}(d_i^{(1)}(x, u))^2 + \sum_{j=1}^{2} \mu_j \left(\rho_j^{(2)}(d_j^{(2)}(x, u))^2 - \tau^T w_j^2\right) = \frac{7}{2} \geq 0.
\]

Thus, hypotheses (ii) and (iii) of Theorem 3.1 are satisfied but

\[
\frac{f_1(x) + x^T z_1}{g_1(x) - x^T v_1} - \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} - L_1(u, p_1) + p_1^T \nabla p_1 L_1(u, p_1) - \mathcal{F}_{x,u} \left[ \left( \frac{f_1(x) + \Omega(x|C_1)}{g_1(x) - \Omega(x|D_1)} \right), \left(\frac{f_2(x) + \Omega(x|C_2)}{g_2(x) - \Omega(x|D_2)}\right) \right] = 0 < 0 \quad \text{at} \quad x = 1.
\]

That is, $(K \times Q) - (\mathcal{F}, \alpha, \rho, d)$-type $I$ convexity of

\[
\left(\frac{f_1(\cdot) + (\cdot)^T z_1}{g_1(\cdot) - (\cdot)^T v_1}, \frac{f_2(\cdot) + (\cdot)^T z_2}{g_2(\cdot) - (\cdot)^T v_2}\right), \quad (h_1(\cdot), \tau) + (\cdot)^T w_1^2, \quad (h_2(\cdot), \tau) + (\cdot)^T w_2^2
\]

is not satisfied. Also, the result of Theorem 3.1 does not hold.

\[ \square \]
4. Wolfe Type Dual

Consider the following Wolfe type higher order dual model for (SIFP):

\[
\text{(WD)} \quad K - \max \left[ \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} + L_1(u, p_1) - p_1^T \nabla_p L_1(u, p_1), \ldots, \frac{f_k(u) + u^T z_k}{g_k(u) - u^T v_k} + L_k(u, p_k) \right]
\]

subject to

\[
\sum_{i=1}^{k} \lambda_i \left[ \nabla_x \left( \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right) + \nabla_p L_i(u, p_i) \right] + \sum_{j=1}^{m} \mu_j \left[ \nabla_x (h_j(u, \tau) + u^T w_j + \tau^T w_j^2) \right. \\
+ \nabla_q S_j(u, q_j) \right] = 0, \quad (4.1)
\]

\[
\sum_{j=1}^{m} \mu_j \left[ h_j(u, \tau) + u^T w_j + \tau^T w_j^2 + S_j(u, q_j) - q_j^T \nabla_q S_j(u, q_j) \right] \geq 0, \quad (4.2)
\]

\[z_i \in C_i, \; v_i \in D_i, \; w_j \in E_j, \; w_j^2 \in M_j, \; i \in \mathcal{I}, \; j \in \mathcal{J}, \; \tau \in T \text{ and } \nu \in \text{int } K^* \times \text{int } Q^*, \; (\lambda, \mu) \neq (0, 0).
\]

**Theorem 4.1 (Weak duality).** Let \( x \) and \((u, v, w^1, w^2, \lambda, \mu, z, p, q)\) be feasible for the problems (SIFP) and (WD), respectively. Let a sublinear functional (in third variable) be \( \mathcal{F} : B \times B \times \mathbb{R}^n \to \mathbb{R} \). Also, assume that

(i) \( \left( \frac{f_1(\cdot) + (\cdot)^T z_1}{g_1(\cdot) - (\cdot)^T v_1}, \ldots, \frac{f_k(\cdot) + (\cdot)^T z_k}{g_k(\cdot) - (\cdot)^T v_k} \right) \) is higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, \beta)\)-type I convex at \( u \) with respect to \( L \) and \( S \),

(ii) \( K \supseteq \mathbb{R}^k_+, \; Q \supseteq \mathbb{R}^m_+ \) and

(iii) \( \sum_{i=1}^{k} \lambda_i \rho_i^{(1)} \left( d_i^{(1)}(x, u) \right)^2 + \sum_{j=1}^{m} \mu_j \{ \rho_j^{(2)} \left( d_j^{(2)}(x, u) \right)^2 - \tau^T w_j^2 \} \geq 0. \)

Then

\[
\left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} + L_1(u, p_1) - p_1^T \nabla_p L_1(u, p_1), \ldots, \frac{f_k(u) + u^T z_k}{g_k(u) - u^T v_k} + L_k(u, p_k) - p_k^T \nabla_p L_k(u, p_k) \right)
\]

\[\left( f_1(x) + \Omega(x|C_1), \ldots, f_k(x) + \Omega(x|C_k) \right) = \mathcal{F}_{x,u} \left( \sum_{i=1}^{k} \lambda_i \left[ \nabla_x \left( \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right) + \nabla_p L_i(u, p_i) \right] \right) + \sum_{i=1}^{k} \lambda_i \rho_i^{(1)} \left( d_i^{(1)}(x, u) \right)^2 \right) \geq K \setminus \{0\}. \quad (4.3)
\]

**Proof.** It follows from hypotheses (i) and (ii) and sublinearity of functional \( \mathcal{F} \) that

\[
\sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} - \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} - L_i(u, p_i) + p_i^T \nabla_p L_i(u, p_i) \right]
\]

\[
\geq \mathcal{F}_{x,u} \left( \alpha(x, u) \sum_{i=1}^{k} \lambda_i \left[ \nabla_x \left( \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right) + \nabla_p L_i(u, p_i) \right] \right) + \sum_{i=1}^{k} \lambda_i \rho_i^{(1)} \left( d_i^{(1)}(x, u) \right)^2 \right) + \sum_{j=1}^{m} \mu_j \left[ (-h_j(u, \tau) + u^T w_j^2) - S_j(u, q_j) + q_j^T \nabla_q S_j(u, q_j) \right] \geq K \setminus \{0\}. \quad (4.4)
\]

\[ \geq \mathcal{F}_{x,u} \left[ \alpha(x,u) \sum_{j=1}^{m} \mu_j \left\{ \nabla_x (h_j(u, \tau) + u^T w_j^1) + \nabla_q S_j(u, q_j) \right\} \right] + \sum_{j=1}^{m} \mu_j \rho_j^{(2)} \left( d_j^{(2)}(x,u) \right)^2. \] (4.5)

Using (4.2) in (4.5) and then adding with (4.4), we get
\[ \sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} - \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} - L_i(u, p_i) + p_i^T \nabla_p L_i(u, p_i) \right] \geq \mathcal{F}_{x,u} \left[ \alpha(x,u) \sum_{i=1}^{k} \lambda_i \left\{ \nabla_x \left( \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right) + \nabla_p L_i(u, p_i) \right\} + \sum_{j=1}^{m} \mu_j \left\{ \nabla_x (h_j(u, \tau) + u^T w_j^1) + \nabla_q S_j(u, q_j) \right\} \right]. \]

It follows from the hypothesis (iii) and sublinearity of \( \mathcal{F} \) that
\[ \sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} - \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} - L_i(u, p_i) + p_i^T \nabla_p L_i(u, p_i) \right] \geq \mathcal{F}_{x,u} \left[ \alpha(x,u) \left\{ \sum_{i=1}^{k} \lambda_i \left\{ \nabla_x \left( \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} \right) + \nabla_p L_i(u, p_i) \right\} + \sum_{j=1}^{m} \mu_j \left\{ \nabla_x (h_j(u, \tau) + u^T w_j^1) + \nabla_q S_j(u, q_j) \right\} \right\} \right]. \]

Further, applying inequality (4.1) and using \( \mathcal{F}_{x,u}(0) = 0 \), we get
\[ \sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} - \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} - L_i(u, p_i) + p_i^T \nabla_p L_i(u, p_i) \right] \geq 0. \] (4.6)

Now, if possible, suppose that
\[ \left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} + L_1(u, p_1) - p_1^T \nabla_p L_1(u, p_1), \ldots, \frac{f_k(u) + u^T z_k}{g_k(u) - u^T v_k} + L_k(u, p_k) - p_k^T \nabla_p L_k(u, p_k) \right) - \left( \frac{f_1(x) + \Omega(x|C_1)}{g_1(x) - \Omega(x|D_1)}, \ldots, \frac{f_k(x) + \Omega(x|C_k)}{g_k(x) - \Omega(x|D_k)} \right) \in K \setminus \{0\}. \]

From \( \lambda \in \text{int} \ K^* \), we get
\[ \sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} + L_i(u, p_i) - p_i^T \nabla_p L_i(u, p_i) - \frac{f_i(x) + \Omega(x|C_i)}{g_i(x) - \Omega(x|D_i)} \right] > 0. \] (4.7)

Since \( x^T z_i \leq \Omega(x|C_i), x^T v_i \leq \Omega(x|D_i) \) and \( \lambda \in \text{int} \ K^* \subseteq \text{int} \mathbb{R}^k_+ \), therefore
\[ \sum_{i=1}^{k} \lambda_i \left( \frac{f_i(x) + \Omega(x|C_i)}{g_i(x) - \Omega(x|D_i)} \right) \geq \sum_{i=1}^{k} \lambda_i \left( \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} \right). \] (4.8)
Finally, using (4.8) in (4.7), we obtain

\[ \sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(u) + u^T z_i}{g_i(u) - u^T v_i} + L_i(u, p_i) - p_i^T \nabla_{p_i} L_i(u, p_i) - \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} \right] > 0 \]

which contradicts (4.6). This proves the theorem.

\[ \square \]

**Theorem 4.2** (Strong duality). Let \( \hat{x} \in B \) be a weakly efficient solution of \((\text{SIFP})\) and the suitable constraint qualification be satisfied at \( \hat{x} \). Then, there exist \( \lambda = (\lambda_1, \ldots, \lambda_k) \in \text{int } K^* \), \( \hat{\mu} = (\hat{\mu}_1, \ldots, \hat{\mu}_m) \in \text{int } Q^* \) and \( (\lambda, \hat{\mu}) \neq (0, 0) \) such that \( (\hat{x}, \hat{v}, \hat{w}^1, \hat{w}^2, \hat{\lambda}, \hat{\mu}, \hat{z}, \hat{p}, \hat{q}) = 0 \) is a feasible solution of \((\text{WD})\) and respective objective function values are same, provided \( L_i(\hat{x}, 0) = 0 \), \( S_i(\hat{x}, 0) = 0 \), \( \nabla_{\hat{p}_i} L_i(\hat{x}, 0) = 0 \) and \( \nabla_{\hat{q}_j} S_j(\hat{x}, 0) = 0 \) \( i \in I, j \in J \). Moreover, if all assumptions of Theorem 4.1 are satisfied for every feasible point \( \hat{x} \) of \((\text{SIFP})\) and \((\hat{v}, \hat{w}^1, \hat{w}^2, \hat{\lambda}, \hat{\mu}, \hat{z}, \hat{p}, \hat{q}) \) of \((\text{WD})\), then \((\hat{x}, \hat{v}, \hat{w}^1, \hat{w}^2, \hat{\lambda}, \hat{\mu}, \hat{z}, \hat{p} = 0, \hat{q} = 0) \) is an efficient solution of \((\text{WD})\).

**Proof.** From the subdifferentiability of support functions, for \( \hat{z}_i \in \partial \Omega(\hat{x}|C_i) \), \( \hat{v}_i \in \partial \Omega(\hat{x}|D_i) \), \( \hat{w}^1_j \in \partial \Omega(\hat{x}|E_j) \) and \( \hat{w}^2_j \in \partial \Omega(\hat{x}|M_j) \), we get

\[ \Omega(\hat{x}|C_i) = \hat{x}^T \hat{z}_i \Omega(\hat{x}|D_i) = \hat{x}^T \hat{v}_i \Omega(\hat{x}|E_j) = \hat{x}^T \hat{w}^1_j \quad \text{and} \quad \Omega(\hat{x}|M_j) = \hat{x}^T \hat{w}^2_j. \]  \hspace{1cm} (4.9)

It further follows from Theorem 2.7 that

\[ \sum_{i=1}^{k} \hat{\lambda}_i \nabla \left( \frac{f_i(\hat{x}) + \hat{x}^T \hat{z}_i}{g_i(\hat{x}) - \hat{x}^T \hat{v}_i} \right) + \sum_{j=1}^{m} \hat{\mu}_j \nabla \left( h_j(\hat{x}, \hat{t}) + \hat{x}^T \hat{w}_j^1 + \hat{t}^T \hat{w}_j^2 \right) = 0 \quad \text{and} \]

\[ \sum_{j=1}^{m} \hat{\mu}_j \left( h(\hat{x}, \hat{t}) + \hat{x}^T \hat{w}_j^1 + \hat{t}^T \hat{w}_j^2 \right) = 0 \]

where \( (\hat{\lambda}, \hat{\mu}) \in \text{int } K^* \times \text{int } Q^*, (\hat{\lambda}, \hat{\mu}) \neq (0, 0) \). Clearly \( L_i(\hat{x}, 0) = 0 \), \( S_i(\hat{x}, 0) = 0 \), \( \nabla_{\hat{p}_i} L_i(\hat{x}, 0) = 0 \), \( \nabla_{\hat{q}_j} S_j(\hat{x}, 0) = 0 \), imply that \( (\hat{x}, \hat{v}, \hat{w}^1, \hat{w}^2, \hat{\lambda}, \hat{\mu}, \hat{z}, \hat{p} = 0, \hat{q} = 0) \) is feasible for \((\text{WD})\) and respective values of objective functions of \((\text{SIFP})\) and \((\text{WD})\) are equal.

Now, on contrary, suppose that \( (\hat{x}, \hat{v}, \hat{w}^1, \hat{w}^2, \hat{\lambda}, \hat{\mu}, \hat{z}, \hat{p} = 0, \hat{q} = 0) \) is not a weak efficient solution of \((\text{WD})\), then there exists a feasible point \((u, v, w^1, w^2, z, \mu, p, q) \) of \((\text{WD})\) such that

\[ \left[ \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} + L_1(u, p_1) - p_1^T \nabla_{p_1} L_1(u, p_1), \ldots, \frac{f_k(u) + u^T z_k}{g_k(u) - u^T v_k} + L_k(u, p_k) - p_k^T \nabla_{p_k} L_k(u, p_k) \right] \]

\[ \left. \quad - \left[ \frac{f_1(\hat{x}) + \hat{x}^T \hat{z}_1}{g_1(\hat{x}) - \hat{x}^T \hat{v}_1} + L_1(\hat{x}, \hat{p}_1) - \hat{p}_1^T \nabla_{\hat{p}_1} L_1(\hat{x}, \hat{p}_1), \ldots, \frac{f_k(\hat{x}) + \hat{x}^T \hat{z}_k}{g_k(\hat{x}) - \hat{x}^T \hat{v}_k} + L_k(\hat{x}, \hat{p}_k) \right] \right\} \in K \setminus \{0\}. \]

Further, using \( \hat{p} = 0 \) and (4.9), we get

\[ \left[ \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} + L_1(u, p_1) - p_1^T \nabla_{p_1} L_1(u, p_1), \ldots, \frac{f_k(u) + u^T z_k}{g_k(u) - u^T v_k} + L_k(u, p_k) - p_k^T \nabla_{p_k} L_k(u, p_k) \right] \]

\[ \left. \quad - \left[ \frac{f_1(\hat{x}) + \Omega(\hat{x}^T z_1)}{g_1(\hat{x}) - \Omega(\hat{x}^T v_1)}, \ldots, \frac{f_k(\hat{x}) + \Omega(\hat{x}^T z_k)}{g_k(\hat{x}) - \Omega(\hat{x}^T v_k)} \right] \right\} \in K \setminus \{0\}. \]

This contradicts the result of the Theorem 4.1. Hence proved.

\[ \square \]
Theorem 4.3 (Strict converse duality). Let \( \tilde{x} \) and \((\tilde{u}, \tilde{v}, \tilde{w}^1, \tilde{w}^2, \tilde{\lambda}, \tilde{\mu}, \tilde{z}, \tilde{p}, \tilde{q})\) be feasible for the problems (SIFP) and (WD), respectively. Let a sublinear functional (in third variable) be \( F : B \times B \times \mathbb{R}^n \to \mathbb{R} \) such that

(i) \( \left( \frac{f_1(\tilde{u}) + \tilde{w}^T \tilde{z}_i}{g_1(\tilde{u}) - \tilde{u}^T \tilde{v}_i} + L_1(\tilde{u}, \tilde{p}_1) - \tilde{p}_i^T \nabla_{\tilde{p}_i} L_1(\tilde{u}, \tilde{p}_1) - \sum_{j=1}^m \tilde{\mu}_j \{ h_j(\tilde{u}, \tilde{\tau}) + \tilde{\mu}^T \tilde{w}^1_j + \tilde{\mu}^T \tilde{w}^2_j + S_j(\tilde{u}, \tilde{q}_j) \} \right. \)

\[ \left. - \tilde{q}_j^T \nabla_{\tilde{q}_j} S_j(\tilde{u}, \tilde{q}_j) \right\} \cdots \right) \}

\[ \frac{f_k(\tilde{u}) + \tilde{w}^T \tilde{z}_i}{g_k(\tilde{u}) - \tilde{u}^T \tilde{v}_k} + L_k(\tilde{u}, \tilde{p}_k) - \tilde{p}_k^T \nabla_{\tilde{p}_k} L_k(\tilde{u}, \tilde{p}_k) - \sum_{j=1}^m \tilde{\mu}_j \{ h_j(\tilde{u}, \tilde{\tau}) + \tilde{\mu}^T \tilde{w}^1_j + \tilde{\mu}^T \tilde{w}^2_j + S_j(\tilde{u}, \tilde{q}_j) \} \right) \cdots \} \]

(ii) \( \left( \frac{f_1(\tilde{x}) + \tilde{x}^T \tilde{z}_i}{g_1(\tilde{x}) - \tilde{x}^T \tilde{v}_i} \right) \cdots \} \)

\[ \frac{f_k(\tilde{x}) + \tilde{x}^T \tilde{z}_k}{g_k(\tilde{x}) - \tilde{x}^T \tilde{v}_k} \in K \]

(iii) \( K \supseteq \mathbb{R}^k, Q \supseteq \mathbb{R}_+^m \) and

(iv) \( \sum_{i=1}^k \tilde{\lambda}_i \rho_i^{(1)}(d_i^{(1)}(\tilde{x}, \tilde{u}))^2 + \sum_{j=1}^m \tilde{\mu}_j \rho_j^{(2)}(d_j^{(2)}(\tilde{x}, \tilde{u}))^2 \geq 0 \).

Then \( \tilde{x} = \tilde{u} \).

Proof. Let \( \tilde{x} \) and \((\tilde{u}, \tilde{v}, \tilde{w}^1, \tilde{w}^2, \tilde{\lambda}, \tilde{\mu}, \tilde{z}, \tilde{p}, \tilde{q})\) be feasible solutions of the problems (SIFP) and (WD), respectively. Let \( \tilde{x} \neq \tilde{u} \). Then, by the Definition 2.3 and supposition (ii), we have

\[ \sum_{i=1}^k \tilde{\lambda}_i \left[ \frac{f_i(\tilde{x}) + \tilde{x}^T \tilde{z}_i}{g_i(\tilde{x}) - \tilde{x}^T \tilde{v}_i} - \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} - L_i(\tilde{u}, \tilde{p}_i) + \tilde{p}_i^T \nabla_{\tilde{p}_i} L_i(\tilde{u}, \tilde{p}_i) \right] \]

\[ > F_{\tilde{x}, \tilde{u}} \left[ \alpha(\tilde{x}, \tilde{u}) \sum_{i=1}^k \tilde{\lambda}_i \left\{ \nabla_{\tilde{x}} \left( \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} \right) + \nabla_{\tilde{p}_i} L_i(\tilde{u}, \tilde{p}_i) \right\} \right] + \sum_{i=1}^k \tilde{\lambda}_i \rho_i^{(1)}(d_i^{(1)}(\tilde{x}, \tilde{u}))^2. \] (4.10)

\[ \sum_{j=1}^m \tilde{\mu}_j \left[ - \{ h_j(\tilde{u}, \tilde{\tau}) + \tilde{\mu}^T \tilde{w}^1_j \} - S_j(\tilde{u}, \tilde{q}_j) + \tilde{q}_j^T \nabla_{\tilde{q}_j} S_j(\tilde{u}, \tilde{q}_j) \right] \]

\[ > F_{\tilde{x}, \tilde{u}} \left[ \alpha(\tilde{x}, \tilde{u}) \sum_{j=1}^m \tilde{\mu}_j \left\{ \nabla_{\tilde{x}} \left( h_j(\tilde{u}, \tilde{\tau}) + \tilde{\mu}^T \tilde{w}^1_j \right) + \nabla_{\tilde{q}_j} S_j(\tilde{u}, \tilde{q}_j) \right\} \right] + \sum_{j=1}^m \tilde{\mu}_j \rho_j^{(2)}(d_j^{(2)}(\tilde{x}, \tilde{u}))^2 \] (4.11)

where \( \tilde{\lambda} \in \mathbb{R}^k \) and \( \tilde{\mu} \in \mathbb{R}_+^m \). Adding (4.10) and (4.11) and using supposition (iv), we get

\[ \sum_{i=1}^k \tilde{\lambda}_i \left[ \frac{f_i(\tilde{x}) + \tilde{x}^T \tilde{z}_i}{g_i(\tilde{x}) - \tilde{x}^T \tilde{v}_i} - \frac{f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i}{g_i(\tilde{u}) - \tilde{u}^T \tilde{v}_i} - L_i(\tilde{u}, \tilde{p}_i) + \tilde{p}_i^T \nabla_{\tilde{p}_i} L_i(\tilde{u}, \tilde{p}_i) \right] \]

\[ + \sum_{j=1}^m \tilde{\mu}_j \left[ - \{ h_j(\tilde{u}, \tilde{\tau}) + \tilde{\mu}^T \tilde{w}^1_j \} - S_j(\tilde{u}, \tilde{q}_j) + \tilde{q}_j^T \nabla_{\tilde{q}_j} S_j(\tilde{u}, \tilde{q}_j) \right] \]

\[ > \sum_{i=1}^k \tilde{\lambda}_i \left\{ \nabla_{\tilde{x}} \left( f_i(\tilde{u}) + \tilde{u}^T \tilde{z}_i \right) + \nabla_{\tilde{p}_i} L_i(\tilde{u}, \tilde{p}_i) \right\} \]

\[ + \sum_{j=1}^m \tilde{\mu}_j \left\{ \nabla_{\tilde{x}} \left( h_j(\tilde{u}, \tilde{\tau}) + \tilde{\mu}^T \tilde{w}^1_j \right) + \nabla_{\tilde{q}_j} S_j(\tilde{u}, \tilde{q}_j) \right\} \]
It further follows from (4.1) and (4.2), sublinearity of $F$ and $F_{x,u}(0) = 0$ that
\[
\sum_{i=1}^{k} \lambda_i \left[ \frac{f_i(x) + \tilde{x}_i^T \tilde{z}_i}{g_i(x) - \tilde{x}_i^T \tilde{v}_i} - \frac{f_i(u) + \tilde{u}_i^T \tilde{z}_i}{g_i(u) - \tilde{u}_i^T \tilde{v}_i} - L_i(\tilde{u}, \tilde{p}_i) + \tilde{p}_i^T \nabla_{\tilde{u}} L_i(\tilde{u}, \tilde{p}_i) \right] > 0. \tag{4.12}
\]

But hypothesis (i), dual constraint (4.2) and $\tilde{\lambda} > 0$ yield
\[
\sum_{i=1}^{k} \tilde{\lambda}_i \left[ \frac{f_i(x) + \tilde{x}_i^T \tilde{z}_i}{g_i(x) - \tilde{x}_i^T \tilde{v}_i} - \frac{f_i(u) + \tilde{u}_i^T \tilde{z}_i}{g_i(u) - \tilde{u}_i^T \tilde{v}_i} - L_i(\tilde{u}, \tilde{p}_i) + \tilde{p}_i^T \nabla_{\tilde{u}} L_i(\tilde{u}, \tilde{p}_i) \right] \leq 0.
\]

This contradicts the inequality (4.12). Hence proved. \hfill \Box

**Example 4.4.** Let in the problem (SIFP), $f : \mathbb{R} \rightarrow \mathbb{R}^2$, $g : \mathbb{R} \rightarrow \mathbb{R}^2$, and $h : \mathbb{R} \times [-0.5, 0] \rightarrow \mathbb{R}^2$ be given as:
\[
\begin{align*}
  f(x) &= (f_1(x), f_2(x)) = (4x^4 - 1, 3x^2), \\
  g(x) &= (g_1(x), g_2(x)) = (x^4 + 2, x^2 + 2) \text{ and } \\
  h(x, t) &= (h_1(x, t), h_2(x, t)) = (x + 2t, x - t - 1).
\end{align*}
\]

Let the cones be $K = \{(x, y) \in \mathbb{R}^2 : x \geq 0, y \geq 0\}$ and $Q = \{(x, y) \in \mathbb{R}^2 : y \geq 0, 3y \geq -x\}$. Also, suppose
\[
\begin{align*}
  L(u, p) &= (L_1(u, p_1), L_2(u, p_2)) = (-p_1u^2, -2p_2(u + 1) - 1), \\
  S(u, q) &= (S_1(u, q_1), S_2(u, q_2)) = (-5q_1u + 2, q_2u - 4), \\
  d_1^{(1)}(x, y) &= d_1^{(2)}(x, y) = (1 - y)(x^2 - y^2) \text{ and } \\
  d_2^{(1)}(x, y) &= d_2^{(2)}(x, y) = (1 - y^2).
\end{align*}
\]

Let the sublinear functional be $F_{x,u}(b) = -b(x^2 - u^2)^2$ and $\alpha(x, y) = 1$. Let $C_1 = \{0\}$, $C_2 = [-2, 0]$, $D_2 = E_1 = [-1, 0]$, and $D_1 = E_2 = M_1 = M_2 = [0, 1]$ then the support functions be given by
\[
\begin{align*}
  \Omega(x|C_1) &= \{0\}, \quad \Omega(x|C_2) = |x| - x, \quad \Omega(x|D_2) = \Omega(x|E_1) = \frac{|x| - x}{2}, \\
  \Omega(x|D_1) = \Omega(x|E_2) = \frac{|x| + x}{2} \text{ and } \Omega(t|M_1) = \Omega(t|M_2) = \frac{|t| + t}{2}.
\end{align*}
\]

Now, the feasible region for (SIFP) is
\[
S_0 = \left\{ x \in \mathbb{R} : \left(-x - 2t - \frac{|x| - x}{2} + t, -x + t + 1 - \frac{|x| + x}{2}\right) \in Q, \text{ for all } t \in [-0.5, 0] \right\}.
\]

Clearly, 0, -1 $\in S_0$. Also, one can easily verify that for the dual model ( WD), $\beta_2 = (u, v, w^1, w^2, \lambda, \mu, z, p, q) = \left(-1, (0, 0), (-1, 1), (0, 0), \left(6, \frac{3}{4}\right), (1, 2), (0, 0), (2, 0), (0, 2)\right)$ and $\beta_3 = (u, v, w^1, w^2, \lambda, \mu, z, p, q) = \left(0, (0, 0), (-1, 0), (0, 0), \left(1, 2\right), (1, 2), (0, 0), (1, 1), (0, 1)\right)$ are feasible solutions.

**Validation of Theorem 4.1:**

At $u = -1$, for $z = (0, 0)$, $v = (0, 0)$ and $\rho_1^{(1)} = \frac{1}{8}$, $\rho_2^{(1)} = -\frac{1}{2}$, we obtain
\[
\left( \frac{f_1(x) + u^T z_1}{g_1(x) - x^T v_1} - \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} - L_1(u, p_1) + p_1^T \nabla_p, L_1(u, p_1) - \mathcal{F}_{x, u} \left[ \alpha(x, u) \left( \nabla_x \left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} \right) + \nabla_p, L_1(u, p_1) \right) \right] - \rho_1^{(1)} \left( d_1^{(1)}(x, u) \right)^2, \frac{f_2(x) + u^T z_2}{g_2(x) - x^T v_2} - \frac{f_2(u) + u^T z_2}{g_2(u) - u^T v_2} - L_2(u, p_2) \right)
\]
\[
+ p_2^T \nabla_{p_2} L_2(u, p_2) - \mathcal{F}_{x, u} \left[ \alpha(x, u) \left( \nabla_x \left( \frac{f_2(u) + u^T z_2}{g_2(u) - u^T v_2} \right) + \nabla_{p_2} L_2(u, p_2) \right) \right] - \rho_2^{(1)} \left( d_2^{(1)}(x, u) \right)^2 \right) \right)
\]
\[
= \left( \frac{(x^2 - 1)^2(5x^4 + 16x^2 + 2)}{2(x^2 + 2)}, \frac{3x^2}{x^2 + 2} + \frac{2}{3}(x^2 - 1)^2 \right) \in K \setminus \{0\}, \text{ for all } x \in \mathbb{R}. \]

Also, for all \( x \in \mathbb{R}, w_1^1 \in E_1, w_2^1 \in E_2, w_1^2 \in M_1, w_2^2 \in M_2, \tau \in T \) and \( \rho_1^{(2)} = 0, \rho_2^{(2)} = 1 \), we get
\[
\left( \frac{(h_1(u, \tau) + u^T w_1^1) - S_1(u, q_1)}{- S_1(u, q_1)} - q_1^T \nabla_q, S_1(u, q_1) - \mathcal{F}_{x, u} \left[ \alpha(x, u) \left( \nabla_x (h_1(u, \tau) + u^T w_1^1) \right) \right] - \rho_1^{(2)} \left( d_1^{(2)}(x, u) \right)^2, -(h_2(u, \tau) + u^T w_2^1) - S_2(u, p_2) + q_2^T \nabla_q, S_2(u, q_2) \right)
\]
\[
- \mathcal{F}_{x, u} \left[ \alpha(x, u) \left( \nabla_x (h_2(u, \tau) + u^T w_2^1) + \nabla_q, S_2(u, q_2) \right) \right] - \rho_2^{(2)} \left( d_2^{(2)}(x, u) \right)^2 \right) \right)
\]
\[
= \left( -1 + w_1^1 - 2\tau + (6 + w_1^1)(x^2 - 1)^2, 2 + \tau + w_2^1(1 + (x^2 - 1)^2) \right) \in Q \setminus \{0\}. \]

Hence, the hypothesis (i) of Theorem 4.1 hold.

Also, \( \mathbb{R}_+^2 = K, \mathbb{R}_+^2 \subset Q \) and \( \sum_{i=1}^{2} \lambda_i \rho_i^{(1)} \left( d_i^{(1)}(x, u) \right)^2 + \sum_{j=1}^{2} \mu_j \rho_j^{(2)} \left( d_j^{(2)}(x, u) \right)^2 - \tau T w_j^1 = \frac{3}{2}(x^2 - 1)^2 \geq 0. \)

Thus, all the hypotheses of Theorem 4.1 are satisfied. Now for the feasible point (of (WD)) \( \beta_2 \), we get
\[
\left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} - L_1(u, p_1) + p_1^T \nabla_p, L_1(u, p_1), \frac{f_2(u) + u^T z_2}{g_2(u) - u^T v_2} - L_2(u, p_2) + p_2^T \nabla_{p_2} L_2(u, p_2) \right)
\]
\[
- \left( \frac{f_1(x) + \Omega(x|C_1)}{- S_1(u, q_1)}, \frac{f_2(x) + \Omega(x|C_2)}{- S_2(u, p_2)} \right) = \begin{cases} (0, -\frac{1}{2}) \notin K \setminus \{0\} \text{ at } x = -1, \\ (-2, 1) \notin K \setminus \{0\} \text{ at } x = 0. \end{cases} \]

This validates the result of Theorem 4.1 for \( x = 0, -1 \in S_0 \) and \( \beta_2 \) feasible for (WD).

Validation of Theorem 4.3:

For the points \( \beta_2 \) and \( x = -1 \), it has been proved above that the assumptions (ii), (iii) and (iv) of Theorem 4.3 are satisfied. Further,
\[
\left( \frac{f_1(u) + u^T z_1}{g_1(u) - u^T v_1} + L_1(u, p_1) - p_1^T \nabla_p, L_1(u, p_1) - \sum_{j=1}^{2} \mu_j \{ h_j(u, \tau) + u^T w_j^1 + \tau T w_j^2 + S_j(u, q_j) - q_j^T \nabla_q, S_j(u, q_j) \}, \right)
\]
\[
\left\{ \frac{f_2(u) + u^T z_2}{g_2(u) - u^T v_2} + L_2(u, p_2) - p_2^T \nabla_{p_2} L_2(u, p_2) - \sum_{j=1}^{2} \mu_j \{ h_j(u, \tau) + u^T w_j^1 + \tau T w_j^2 + S_j(u, q_j) - q_j^T \nabla_q, S_j(u, q_j) \} \right\}
\]
\[
- \left( \frac{f_1(x) + \bar{x}^T z_1}{g_1(x) - x^T v_1}, \frac{f_2(x) + x^T z_2}{g_2(x) - x^T v_2} \right) = (0, -1) \notin K. \]

Hence, the assumption (i) also holds at \( x = u = -1 \). This completes the validation of Theorem 4.3.
Without the assumption (i) of Theorem 4.1:

For any \( \rho_1^{(1)}, \rho_2^{(1)}, \rho_1^{(2)}, \rho_2^{(2)} \in \mathbb{R} \), at \( \beta_3 \), for (WD),

\[
\sum_{i=1}^{2} \lambda_i \rho_i^{(1)} \left( d_i^{(1)}(x, u) \right)^2 + \sum_{j=1}^{2} \mu_j \left( \rho_j^{(2)} \left( d_j^{(2)}(x, u) \right)^2 - \tau^T w_j^2 \right) = 0
\]

and \( \mathbb{R}_+^2 = K, \mathbb{R}_+^2 \subset Q \). Therefore, assumption (ii) and (iii) of Theorem 4.1 are satisfied but at \( x = 0 \),

\[
\begin{align*}
- (h_1(u, \tau) + u^T w_1^1) - S_1(u, q_1) + q_1^T \nabla_{q_1} S_1(u, q_1) - F_{x, u} \left[ \alpha(x, u) \left( \nabla_x (h_1(u, \tau) + u^T w_1^1) + \nabla_{q_1} S_1(u, q_1) \right) - \rho_1^{(2)} \left( d_1^{(2)}(x, u) \right)^2 \right]
&= -7 - 2\tau < 0, \text{ for all } \tau \in [-0.5, 0].
\end{align*}
\]

Hence, the pair \( \left( \frac{f_1(\cdot)}{g_1(u)} + \frac{f_2(\cdot)}{g_2(u)} \right) = (h_1(\cdot), \tau) + (\cdot)^T w_1^1, \frac{f_2(\cdot)}{g_2(u)} - (\cdot)^T \frac{v_2}{|v_2|} \) is not \( (K \times Q - (F, \alpha, \rho, d)) \)-type \( I \) convex. On the other hand, at \( x = 0 \) and \( \beta_3 \),

\[
\begin{align*}
\left( \frac{f_1(u)}{g_1(u)} + u^T z_1 - L_1(u, p_1) - p_1^T \nabla_{p_1} L_1(u, p_1), \frac{f_2(u)}{g_2(u)} + u^T z_2 - L_2(u, p_2) - p_2^T \nabla_{p_2} L_2(u, p_2) \right)
&= \left( \left( \frac{f_1(u)}{g_1(u)} + \Omega(x|C_1) \right) - \frac{f_2(u)}{g_2(u)} - \Omega(x|D_2) \right) = (0, 1) \in K \setminus \{0\}.
\end{align*}
\]

This shows the significance of assumption (i) in Theorem 4.1, without which the result may not satisfy. \( \square \)

5. Schaible Type Dual

For the (SIFP) model, consider the following Schaible type higher order dual:

\((SD)\) \( K = \max \left( \eta_1, \eta_2, \ldots, \eta_k \right) \)

subject to

\[
\begin{align*}
\sum_{i=1}^{k} \lambda_i \nabla_x (f_i(u) + u^T z_i - \eta_i (g_i(u) - u^T v_i)) + \sum_{j=1}^{m} \mu_j \nabla_x \left( h_j(u, \tau) + u^T w_j^1 + \tau^T w_j^2 \right)
&+ \sum_{i=1}^{k} \lambda_i \nabla_{p_i} [G_i(u, p_i) - \eta_i L_i(u, p_i)] + \sum_{j=1}^{m} \mu_j \nabla_{q_j} S_j(u, q_j) = 0, \quad (5.1)
\end{align*}
\]

\[
\begin{align*}
\sum_{i=1}^{k} \lambda_i \left( f_i(u) + u^T z_i - \eta_i (g_i(u) - u^T v_i) + G_i(u, p_i) - \eta_i L_i(u, p_i) \right)
- p_i^T \nabla_{p_i} (G_i(u, p_i) - \eta_i L_i(u, p_i)) \geq 0, \quad (5.2)
\end{align*}
\]

\[
\begin{align*}
\sum_{j=1}^{m} \mu_j \left( h_j(u, \tau) + u^T w_j^1 + \tau^T w_j^2 + S_j(u, q_j) - q_j^T \nabla_{q_j} S_j(u, q_j) \right) \geq 0, \quad (5.3)
\end{align*}
\]

\( z_i \in C_i, v_i \in D_i, w_j \in E_j, \eta \in \mathbb{R}_k^k, i \in \bar{I}, j \in \bar{J}, (\lambda, \mu) \in \text{ int } K^* \times \text{ int } Q^*, (\lambda, \mu) \neq (0, 0) \) and \( \tau \in T \).

Throughout this section, we have used \( \rho_i^{(1)} = \left( \rho_f^{(1)}, \rho_g^{(1)} \right) \in \mathbb{R} \times \mathbb{R} \) and \( d_i^{(1)} = \left( d_f^{(1)}, d_g^{(1)} \right) \in \mathbb{R} \times \mathbb{R} \).
Theorem 5.1 (Weak duality). Let for every feasible solution $x$ of (SIFP) and $(u, v, w^1, w^2, \lambda, \mu, \eta, p, q)$ of (SD), $F: B \times B \times \mathbb{R}^n \to \mathbb{R}$ be a sublinear functional (in third variable) and

(i) $\left( (f_1(\cdot) + (\cdot)^T z_1, \ldots, f_k(\cdot) + (\cdot)^T z_k, (h_1(\cdot, \tau) + (\cdot)^T w^1_1, \ldots, h_m(\cdot, \tau) + (\cdot)^T w^1_m) \right)$ be higher order $(K \times Q)$ - $(F, \alpha, \rho, d)$-type I convex with respect to $G$ and $S$,

(ii) $\left( (-\eta(\cdot) - (\cdot)^T v_1), \ldots, -q_k(\cdot) - (\cdot)^T v_k, (h_1(\cdot, \tau) + (\cdot)^T w^1_1, \ldots, h_m(\cdot, \tau) + (\cdot)^T w^1_m) \right)$ be higher order $(K \times Q) - (F, \alpha, \rho, d)$-type I convex with respect to $-\eta L$ and $S$,

(iii) $\sum_{i=1}^k \lambda_i \left\{ \rho_f^{(1)} \left( d^{(1)}(x, u) \right)^2 + \rho_g^{(1)} \left( d^{(1)}(x, u) \right)^2 \right\} + \sum_{j=1}^m \mu_j \left\{ \rho_f^{(2)} \left( d^{(2)}(x, u) \right)^2 - \tau^T w^2 \right\} \geq 0$ and

(iv) $K \supseteq \mathbb{R}^k_+$, $Q \supseteq \mathbb{R}^m_+$.

Then

$$\left( (\eta_1, \ldots, \eta_k) - \left( \frac{f_1(x) + \Omega(x|C_1)}{g_1(x) - \Omega(x|D_1)}, \ldots, \frac{f_k(x) + \Omega(x|C_k)}{g_k(x) - \Omega(x|D_k)} \right) \right) \notin K \setminus \{0\}. \tag{5.4}$$

Proof. Let if possible (5.4) be not true. Then by hypothesis (iv), $\lambda \in \text{int } K^* \subset \text{int } \mathbb{R}^k_+$, we have

$$\sum_{i=1}^k \lambda_i \left[ \eta_i - \frac{f_i(x) + \Omega(x|C_i)}{g_i(x) - \Omega(x|D_i)} \right] > 0. \tag{5.5}$$

Since $x^T z_i \leq \Omega(x|C_i)$ and $x^T v_i \leq \Omega(x|D_i)$, we obtain

$$f_i(x) + \Omega(x|C_i) - \frac{f_i(x) + x^T z_i}{g_i(x)} \geq 0.$$  \tag{5.6}

It follows from $\lambda_i > 0$, for all $i$, that

$$\sum_{i=1}^k \lambda_i \left[ \frac{f_i(x) + \Omega(x|C_i)}{g_i(x) - \Omega(x|D_i)} - \frac{f_i(x) + x^T z_i}{g_i(x) - x^T v_i} \right] \geq 0. \tag{5.6}$$

Further, adding (5.5) and (5.6), we get

$$\sum_{i=1}^k \lambda_i \left[ \eta_i (g_i(x) - x^T v_i) - (f_i(x) + x^T z_i) \right] > 0. \tag{5.7}$$

Now, for $\lambda \in \text{int } K^*$ and $\mu \in \text{int } Q^*$, hypotheses (i) and (ii) imply

$$\sum_{i=1}^k \lambda_i \left[ f_i(x) + x^T z_i - (f_i(u) + u^T z_i) - G_i(u, p_i) + p_i^T \nabla_p G_i(u, p_i) \right. \tag{5.8}$$

$$\left. - \mathcal{F}_{x,u} \left( \alpha(x, u) \nabla_x (f_i(u) + u^T z_i) + \nabla_p G_i(u, p_i) \right) - \rho_f^{(1)} \left( d^{(1)}(x, u) \right)^2 \right] \geq 0.$$  \tag{5.8}

$$\sum_{i=1}^k \lambda_i \left[ \eta_i (-g_i(x) - x^T v_i) + (g_i(u) - u^T v_i) + \eta_i L_i(u, p_i) - \eta_i p_i^T \nabla_p L_i(u, p_i) \right. \tag{5.9}$$

$$\left. - \mathcal{F}_{x,u} \left( -\eta_i \alpha(x, u) \left( \nabla_x (g_i(u) - u^T v_i) + \nabla_p L_i(u, p_i) \right) \right) - \rho_g^{(1)} \left( d^{(1)}(x, u) \right)^2 \right] \geq 0.$$  \tag{5.9}

$$\sum_{j=1}^m \mu_j \left[ -(h_j(u) + u^T w^1_j) - S_j(u, q_j) + q_j^T \nabla_q S_j(u, q_j) \right. \tag{5.10}$$

$$\left. - \mathcal{F}_{x,u} \left( \alpha(x, u) \left( \nabla_x (h_j(u) + u^T w^1_j) + \nabla_q S_j(u, q_j) \right) \right) - \sum_{j=1}^m \mu_j \rho_j^{(2)} \left( d^{(2)}(x, u) \right)^2 \right] \geq 0.$$  \tag{5.10}
From $\lambda_i > 0$, for all $i$ and sublinearity of $\mathcal{F}$, the inequalities (5.8) and (5.9) yield
\[
\sum_{i=1}^{k} \lambda_i \left\{ f_i(x) + x^T z_i - (f_i(u) + u^T z_i) - G_i(u, p_i) + p_i^T \nabla p_i G_i(u, p_i) \right. \\
- \eta_i(g_i(x) - x^T v_i) + \eta_i(g_i(u) - u^T v_i) + \eta_i L_i(u, p_i) - \eta_i p_i^T \nabla p_i L_i(u, p_i) \left\} \geq \sum_{i=1}^{k} \lambda_i \mathcal{F}_{x,u} \left( \alpha(x,u)(\nabla_x f_i(u) + u^T z_i) + \nabla p_i G_i(u, p_i) - \eta_i(\nabla_x g_i(u) - u^T v_i) \right. \\
+ \nabla p_i L_i(u, p_i)) \left\} + \sum_{i=1}^{k} \lambda_i \left\{ \rho_{f_i}^{(1)} \left( d_{f_i}^{(1)}(x,u) \right)^2 + \rho_{g_i}^{(1)} \left( d_{g_i}^{(1)}(x,u) \right)^2 \right\}.
\]

Further using (5.2), we get
\[
\sum_{i=1}^{k} \lambda_i \left\{ f_i(x) + x^T z_i - \eta_i(g_i(x) - x^T v_i) \right\} \geq \sum_{i=1}^{k} \lambda_i \mathcal{F}_{x,u} \left( \alpha(x,u)(\nabla_x f_i(u) + u^T z_i) + \nabla p_i G_i(u, p_i) - \eta_i(\nabla_x g_i(u) - u^T v_i) \right. \\
+ \nabla p_i L_i(u, p_i)) \left\} + \sum_{i=1}^{k} \lambda_i \left\{ \rho_{f_i}^{(1)} \left( d_{f_i}^{(1)}(x,u) \right)^2 + \rho_{g_i}^{(1)} \left( d_{g_i}^{(1)}(x,u) \right)^2 \right\}.
\]

The inequality (5.10) together with sublinearity of $\mathcal{F}$ yield
\[
\sum_{j=1}^{m} \mu_j \left\{ -(h_j(u) + u^T w_j^1) - S_j(u, q_j) + q_j^T \nabla q_j S_j(u, q_j) \right\} \geq \mathcal{F}_{x,u} \left( \alpha(x,u) \sum_{j=1}^{m} \mu_j (\nabla_x h_j(u) + u^T w_j^1) + \nabla q_j S_j(u, q_j) \right) + \sum_{j=1}^{m} \mu_j \rho_{h_j}^{(2)} \left( d_{h_j}^{(2)}(x,u) \right)^2.
\]

It follows from (5.11) and (5.12) and hypothesis (iii) that
\[
\sum_{i=1}^{k} \lambda_i \left\{ f_i(x) + x^T z_i + \eta_i(-g_i(x) - x^T v_i)) \right\} \\
+ \sum_{j=1}^{m} \mu_j \left\{ -(h_j(u) + u^T w_j^1 + \tau^T w_j^2) - S_j(u, q_j) + q_j^T \nabla q_j S_j(u, q_j) \right\} \geq \mathcal{F}_{x,u} \left( \sum_{i=1}^{k} \lambda_i \left\{ (\nabla_x f_i(u) + u^T z_i) + \nabla p_i G_i(u, p_i) - \eta_i(\nabla_x g_i(u) - u^T v_i) \right. \\
+ \nabla p_i L_i(u, p_i)) \right. \\
+ \sum_{j=1}^{m} \mu_j \left\{ (\nabla_x h_j(u) + u^T w_j^1) + \nabla q_j S_j(u, q_j) \right\} \right).
\]

Finally, using (5.1) and (5.3), we get
\[
\sum_{i=1}^{k} \lambda_i \left[ \eta_i(g_i(x) - x^T v_i) - (f_i(x) + x^T z_i) \right] \leq 0.
\]

This contradicts the inequality (5.7). Hence the result.

\[\square\]
**Theorem 5.2** (Strong duality). Let \( \check{x} \) be a weakly efficient solution of (SIFP) and the suitable constraint qualification be satisfied at \( \check{x} \). Then for \( L_i(\check{x}, 0) = G_i(\check{x}, 0) = S_j(\check{x}, 0) = 0 \), \( \nabla_{\hat{p}_i} L_i(\check{x}, 0) = \nabla_{\bar{q}_j} S_j(\check{x}, 0) = \nabla_{\bar{p}_j} \), \( i = 1, 2, \ldots, k, j = 1, 2, \ldots, m \), there exist \((0, 0) \neq (\bar{\lambda}, \bar{\mu}) \in \text{int } K^* \times \text{int } Q^* \), \( \tilde{\eta} \in \mathbb{R}^k_+ \), \( \tilde{z}_i \in C_i, \tilde{v}_i \in D_i, \tilde{w}_i^1 \in E_j, \tilde{w}_i^2 \in M_j, i \in \tilde{I}, j \in \tilde{J} \) such that \((\check{x}, \tilde{v}, \tilde{w}^1, \tilde{w}^2, \lambda, \bar{\mu}, \bar{z}, \tilde{\eta}, \check{\eta} = 0, \check{\eta} = 0) \) is feasible point for (SD) and the objective function values are same for both problems. Moreover, if for every feasible point \( \check{x} \) and \((\check{u}, \check{v}, \check{w}^1, \check{w}^2, \lambda, \bar{\mu}, \bar{z}, \tilde{\eta}, \check{\eta}, \check{\eta} = 0, \check{\eta} = 0) \) of (SIFP) and (SD) respectively, all assumptions of Theorem 5.1 are satisfied then \((\check{x}, \tilde{v}, \tilde{w}^1, \tilde{w}^2, \lambda, \bar{\mu}, \bar{z}, \tilde{\eta}, \check{\eta} = 0, \check{\eta} = 0) \) is an efficient solution of (SD).

**Proof.** It follows on the lines of Theorem 4.2. \( \square \)

**Theorem 5.3** (Strict converse duality). Let \( \check{x} \) be feasible for (SIFP) and \((\check{u}, \check{v}, \check{w}^1, \check{w}^2, \lambda, \bar{\mu}, \bar{z}, \tilde{\eta}, \check{\eta}, \check{\eta} = 0, \check{\eta} = 0) \) be feasible for (SD). Let a sublinear functional values (in third variable) be \( \mathcal{F} : B \times B \times \mathbb{R}^n \to \mathbb{R} \) such that

(i) \((\tilde{\eta}_1, \ldots, \tilde{\eta}_k) - (f_1(\check{x}) + \check{x}^T \check{z}_1, \ldots, f_k(\check{x}) + \check{x}^T \check{z}_k) \in K, \)

(ii) \((f_1(\cdot) + (\cdot)^T \check{z}_1, \ldots, f_k(\cdot) + (\cdot)^T \check{z}_k) + (h_1(\cdot, \check{\eta}) + (\cdot)^T \check{w}_1, \ldots, h_m(\cdot, \check{\eta}) + (\cdot)^T \check{w}_m) \) be strictly higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, \mu, L)\)-type I convex with respect to \( G \) and \( S \),

(iii) \((\tilde{\eta}_1(g_1(\cdot) + (\cdot)^T \check{t}_1), \ldots, \tilde{\eta}_k(g_k(\cdot) + (\cdot)^T \check{t}_k), (h_1(\cdot, \check{\eta}) + (\cdot)^T \check{v}_1, \ldots, h_m(\cdot, \check{\eta}) + (\cdot)^T \check{v}_m) \) be strictly higher order \((K \times Q) - (\mathcal{F}, \alpha, \rho, \mu, L)\)-type I convex with respect to \(-\check{\eta}L \) and \( S \),

(iv) \( \sum_{i=1}^{k} \tilde{\lambda}_i \left\{ \rho_1^{(1)} \left( d_1^{(1)}(\check{x}, \check{u}) \right)^2 + \rho_2^{(1)} \left( d_2^{(1)}(\check{x}, \check{u}) \right)^2 \right\} + \sum_{j=1}^{m} \mu_j \left\{ \rho_1^{(2)} \left( d_1^{(2)}(\check{x}, \check{u}) \right)^2 - \check{z}^T \check{w}_j \right\} \geq 0 \) and \( K \supseteq \mathbb{R}^k_+, Q \supseteq \mathbb{R}^m_+ \).

Then \( \check{x} = \check{u} \).

**Proof.** We will show the proof by contradiction. Let \( \check{x} \neq \check{u} \). Then, by hypotheses (ii) and (iii), we have

\[
\sum_{i=1}^{k} \tilde{\lambda}_i \left[ f_i(\check{x}) + \check{x}^T \check{z}_i - (f_i(\check{u}) + \check{u}^T \check{z}_i) - G_i(\check{u}, \check{p}_i) + \check{p}_i^T \nabla_{\check{p}_i} G_i(\check{u}, \check{p}_i) - \mathcal{F}_{\check{x}, \check{u}} \left( \alpha(\check{x}, \check{u}) (\nabla_{\check{x}} f_i(\check{u}) + \check{u}^T \check{z}_i) + \nabla_{\check{p}_i} G_i(\check{u}, \check{p}_i) \right) - \rho_1^{(i)} \left( d_1^{(i)}(\check{x}, \check{u}) \right)^2 \right] > 0. \tag{5.14}
\]

\[
\sum_{i=1}^{k} \tilde{\lambda}_i \left[ \tilde{\eta}_i (g_i(\check{x}) - \check{x}^T \check{v}_i) + g_i(\check{u}) - \check{u}^T \check{v}_i + \tilde{\eta}_i L_i(\check{u}, \check{p}_i) - \tilde{\eta}_i \check{p}_i^T \nabla_{\check{p}_i} L_i(\check{u}, \check{p}_i) - \mathcal{F}_{\check{x}, \check{u}} \left( \alpha(\check{x}, \check{u}) (-\tilde{\eta}_i (\nabla_{\check{x}} g_i(\check{u}) - \check{u}^T \check{v}_i) + \nabla_{\check{p}_i} L_i(\check{u}, \check{p}_i)) \right) - \rho_1^{(i)} \left( d_1^{(i)}(\check{x}, \check{u}) \right)^2 \right] > 0. \tag{5.15}
\]

\[
\sum_{j=1}^{m} \mu_j \left[ \check{h}_j(\check{u}) + \check{u}^T \check{w}_j - S_j(\check{u}, \check{q}_j) + \check{q}_j^T \nabla_{\check{q}_j} S_j(\check{u}, \check{q}_j) - \mathcal{F}_{\check{x}, \check{u}} \left( \alpha(\check{x}, \check{u}) (\nabla_{\check{x}} h_j(\check{u}) + \check{u}^T \check{w}_j) + \nabla_{\check{q}_j} S_j(\check{u}, \check{q}_j) \right) - \rho_2^{(j)} \left( d_2^{(j)}(\check{x}, \check{u}) \right)^2 \right] > 0. \tag{5.16}
\]

where \( \tilde{\lambda} \in \text{int } K^* \) and \( \tilde{\mu} \in \text{int } Q^* \). From (5.14), (5.15), hypothesis (iv) and sublinearity of \( \mathcal{F} \), we obtain

\[
\sum_{i=1}^{k} \tilde{\lambda}_i \left\{ f_i(\check{x}) + \check{x}^T \check{z}_i - (f_i(\check{u}) + \check{u}^T \check{z}_i) - G_i(\check{u}, \check{p}_i) + \check{p}_i^T \nabla_{\check{p}_i} G_i(\check{u}, \check{p}_i) + \check{p}_i^T \nabla_{\check{p}_i} G_i(\check{u}, \check{p}_i) \right\}
\]


Applying (5.3) in (5.18) and then adding with (5.17), we obtain
\[
> \mathcal{F}_{\bar{x}, \bar{u}} \left( \alpha(\bar{x}, \bar{u}) \sum_{i=1}^{k} \lambda_i \left\{ \left( \nabla_{\bar{x}} f_i(\bar{u}) + \bar{u}^T \bar{z}_i \right) + \nabla_{\bar{x}} \tilde{G}_i(\bar{u}, \tilde{\bar{p}}_i) - \tilde{\eta}_i \left( \nabla_{\bar{x}} \left( g_i(\bar{u}) - \bar{u}^T \tilde{\bar{v}}_i \right) \right) \\
+ \nabla_{\bar{x}} L_i(\bar{u}, \tilde{\bar{p}}_i) \right\} \right) + \sum_{i=1}^{k} \lambda_i \left\{ \rho^{(1)}_{f_i} \left( d_{f_i}^{(1)}(\bar{x}, \bar{u}) \right)^2 + \rho^{(1)}_{g_i} \left( d_{g_i}^{(1)}(\bar{x}, \bar{u}) \right)^2 \right\}.
\]
Now, using (5.2) in the above inequality, we get
\[
> \mathcal{F}_{\bar{x}, \bar{u}} \left( \alpha \sum_{i=1}^{k} \lambda_i \left\{ (\bar{x}, \bar{u}) \left( \nabla_{\bar{x}} f_i(\bar{u}) + \bar{u}^T \bar{z}_i \right) + \nabla_{\bar{x}} \tilde{G}_i(\bar{u}, \tilde{\bar{p}}_i) - \tilde{\eta}_i \left( \nabla_{\bar{x}} \left( g_i(\bar{u}) - \bar{u}^T \tilde{\bar{v}}_i \right) \right) \\
+ \nabla_{\bar{x}} L_i(\bar{u}, \tilde{\bar{p}}_i) \right\} \right) + \sum_{i=1}^{k} \lambda_i \left\{ \rho^{(1)}_{f_i} \left( d_{f_i}^{(1)}(\bar{x}, \bar{u}) \right)^2 + \rho^{(1)}_{g_i} \left( d_{g_i}^{(1)}(\bar{x}, \bar{u}) \right)^2 \right\}.
\]
Since \( \hat{\mu} \in \text{int } Q^* \subseteq \text{int } \mathbb{R}_+^m \), and \( \mathcal{F} \) is sublinear, the inequality (5.16) further yields
\[
> \sum_{j=1}^{m} \mu_j \left\{ -\left( h_j(\bar{u}) + \bar{u}^T \bar{w}_j \right) - S_j(\bar{u}, \bar{q}_j) + \bar{q}_j^T \nabla_{\bar{q}} S_j(\bar{u}, \bar{q}_j) \right\} \\
> \mathcal{F}_{\bar{x}, \bar{u}} \left( \alpha \sum_{j=1}^{m} \mu_j \left\{ \nabla_{\bar{x}} \left( h_j(\bar{u}) + \bar{u}^T \bar{w}_j \right) + \nabla_{\bar{q}} S_j(\bar{u}, \bar{q}_j) \right\} \right) + \sum_{j=1}^{m} \mu_j \rho_j^{(2)} \left( d_j^{(2)}(\bar{x}, \bar{u}) \right)^2.
\]
Applying (5.3) in (5.18) and then adding with (5.17), we obtain
\[
> \sum_{i=1}^{k} \lambda_i \left\{ f_i(\bar{x}) + \bar{x}^T \bar{z}_i + \tilde{\eta}_i \left( g_i(\bar{x}) - \bar{x}^T \tilde{\bar{v}}_i \right) \right\} \\
> \mathcal{F}_{\bar{x}, \bar{u}} \left( \alpha(\bar{x}, \bar{u}) \sum_{i=1}^{k} \lambda_i \left\{ \nabla_{\bar{x}} f_i(\bar{u}) + \bar{u}^T \bar{z}_i \right\} + \nabla_{\bar{x}} G_i(\bar{u}, \bar{p}_i) - \eta_i \left( \nabla_{\bar{x}} \left( g_i(\bar{u}) - \bar{u}^T \tilde{\bar{v}}_i \right) \right) \\
+ \nabla_{\bar{x}} L_i(\bar{u}, \bar{p}_i) \right\} + \mathcal{F}_{\bar{x}, \bar{u}} \left( \alpha(\bar{x}, \bar{u}) \sum_{j=1}^{m} \mu_j \left\{ \nabla_{\bar{x}} \left( h_j(\bar{u}) + \bar{u}^T \bar{w}_j \right) + \nabla_{\bar{q}} S_j(\bar{u}, \bar{q}_j) \right\} \right) \\
+ \sum_{i=1}^{k} \lambda_i \left\{ \rho^{(1)}_{f_i} \left( d_{f_i}^{(1)}(\bar{x}, \bar{u}) \right)^2 + \rho^{(1)}_{g_i} \left( d_{g_i}^{(1)}(\bar{x}, \bar{u}) \right)^2 \right\} \right) + \sum_{j=1}^{m} \mu_j \left\{ \rho_j^{(2)} \left( d_j^{(2)}(\bar{x}, \bar{u}) \right)^2 - \bar{z}_j^T \bar{w}_j \right\}.
\]
Further, using hypothesis (iv), dual constraint (5.1) and \( \mathcal{F}_{\bar{x}, \bar{u}}(0) = 0 \), we have
\[
> \sum_{i=1}^{k} \lambda_i \left[ \eta_i(g_i(\bar{x}) - \bar{x}^T \bar{v}_i) - (f_i(\bar{x}) + \bar{x}^T \bar{z}_i) \right] < 0.
\]
But from hypothesis (i) and \( \hat{\lambda} \in \text{int } K^* \), we have
\[
\sum_{i=1}^{k} \lambda_i [f_i(\bar{x}) + \bar{x}^T \bar{z}_i - \eta_i(g_i(\bar{x}) - \bar{x}^T \bar{v}_i)] \leq 0,
\]
which contradicts (5.20). Hence the result. \( \square \)
Example 5.4. Let in the problem (SIFP), \( f : \mathbb{R} \to \mathbb{R}^2 \), \( g : \mathbb{R} \to \mathbb{R}^2 \), and \( h : \mathbb{R} \times [-2, -1] \to \mathbb{R}^2 \) be given as:
\[
\begin{align*}
  f(x) &= (f_1(x), f_2(x)) = (e^{x-1}, x^2 + 12), \\
  g(x) &= (g_1(x), g_2(x)) = (x^2 + 1, 13(2 + x^2)) \text{ and} \\
  h(x, t) &= (h_1(x, t), h_2(x, t)) = (x + 3t, x + t - 1).
\end{align*}
\]
Let
\[
\begin{align*}
  K &= \{(x, y) \in \mathbb{R}^2 : x \geq 0, y \geq -2x\}, \\
  Q &= \{(x, y) \in \mathbb{R}^2 : x \geq 0, y \geq 0\}, \\
  G(u, p) &= (G_1(u, p_1), G_2(u, p_2)) = (p_1 - u^4, -(p_2 u^2 + 5)), \\
  L(u, p) &= (L_1(u, p_1), L_2(u, p_2)) = (p_1 u^2 + 5, e^{-p_2 u}), \\
  S(u, q) &= (S_1(u, q_1), S_2(u, q_2)) = \left(q_1(u + 1)^2 + 2, q_2(u - 1) + 3\right).
\end{align*}
\]
Further, let \( \alpha(x, y) = (2 - y)^2 \) and \( \mathcal{F}_{x,u}(b) = -bx^2u. \) Consider
\[
C_1 = [0, 2] = M_2, C_2 = D_2 = E_2 = [-1, 1] \text{ and } D_1 = E_1 = M_1 = [-2, 0].
\]
Then, their support functions will be
\[
\begin{align*}
  \Omega(x|C_1) &= x + |x|, \quad \Omega(x|C_2) = \Omega(x|D_2) = \Omega(x|E_2) = |x|, \quad \Omega(t|M_1) = |t| - t, \\
  \Omega(x|D_1) &= \Omega(x|E_1) = |x| - x \quad \text{and} \quad \Omega(t|M_2) = t + |t|.
\end{align*}
\]
The feasible set of the given problem:
\[
S_0 = \left\{ x \in \mathbb{R} : \left(-2t - |x| - |t|, 1 - x - |x| - 2t - |t|\right) \in Q, \text{ for all } t \in [-2, -1] \right\} = [-1, 1].
\]
Also the point \( \beta = (u, v, w^1, w^2, \lambda, \mu, z, \eta, p, q) = \left(1, (0, 0), (-1, 1), (-2, 0), (1, 1), \left(\frac{1}{2}, \frac{1}{2}\right), \right) \)
(0, 0), (1, 0), (1, 2), (1, 2) \) satisfies the dual constraints (5.1)–(5.3) and hence feasible for (SD).

Validation of Theorem 5.1:
For \( u = 1 \), taking \( z_1 = z_2 = 0 \), \( \rho^{(1)}_{f_1} = \rho^{(1)}_{f_2} = 1 \) and \( d^{(1)}_{f_1}(x,y) = xy \), \( d^{(1)}_{f_2}(x,y) = y + 1 \), we obtain
\[
\begin{align*}
  \left( f_1(x) + x^T z_1 - (f_1(u) + u^T z_1) - G_1(u, p_1) + p_1^T \nabla_{p_1} G_1(u, p_1) - \mathcal{F}_{x,u}(\alpha(x,u)(\nabla_x(f_1(u) + u^T z_1))
  + \nabla_{p_1} G_1(u, p_1)))) - \rho^{(1)}_{f_1}\left(d^{(1)}_{f_1}(x,y)\right)^2 \right. \\
  \left. + f_2(x) + x^T z_2 - (f_2(u) + u^T z_2) - G_2(u, p_2) + p_2^T \nabla_{p_2} G_2(u, p_2) - \mathcal{F}_{x,u}(\alpha(x,u)(\nabla_x(f_2(u) + u^T z_2))
  + \nabla_{p_2} G_2(u, p_2)))) - \rho^{(1)}_{f_2}\left(d^{(1)}_{f_2}(x,y)\right)^2 \right)
\end{align*}
\]
\[
= (e^{-1} + x^2, 2x^2) \in K \setminus \{0\}, \text{ for all } x \in \mathbb{R}
\]
Also, for \( \eta_1 = 1, \eta_2 = 0, v_1 = v_2 = 0, \rho^{(1)}_{g_1} = 1, \rho^{(1)}_{g_2} = 0 \) and \( d^{(1)}_{g_1}(x,y) = x(y - 1) \), \( d^{(1)}_{g_2}(x,y) = x + y \), we get
\[
\begin{align*}
  \left( \eta_1(-g_1(x) - x^T v_1) + g_1(u) - u^T v_1) + \eta_1 L_1(u, p_1) - \eta_1 p_1^T \nabla_{p_1} L_1(u, p_1) - \mathcal{F}_{x,u}(\eta_1 \alpha(x,u)(\nabla g_1(u)
  - v_1) + \nabla_{p_1} L_1(u, p_1)))) - \rho^{(1)}_{g_1}\left(d^{(1)}_{g_1}(x,y)\right)^2 \right. \\
  \left. + \eta_2 L_2(u, p_2) - \mathcal{F}_{x,u}(\eta_2 \alpha(x,u)(\nabla g_2(u) - u^T v_2) + \nabla_{p_2} L_2(u, p_2)))) - \rho^{(1)}_{g_2}\left(d^{(1)}_{g_2}(x,y)\right)^2 \right)
\end{align*}
\]
\[
= (2x^2 + 6, 0) \in K \setminus \{0\}, \text{ for all } x \in \mathbb{R}
\]
and for \( \rho_1^{(2)} = 0, \rho_2^{(2)} = -1, d_1^{(2)}(x, y) = xy, d_2^{(2)}(x, y) = y + 1 \), we have
\[
\left( -(h_1(u, \tau) + u^Tw_1^1) - S_1(u, q_1) + q_1^T\nabla q_1S_1(u, q_1) - F_{x,u}\left( \alpha(x, u) \left( \nabla_x(h_1(u, \tau) + u^Tw_1^1) + \nabla q_1S_1(u, q_1) \right) \right) - \rho_1^{(2)} \left( d_1^{(2)}(x, u) \right)^2, -h_2(u, \tau) + u^Tw_2^1 - S_2(u, q_2) + q_2^T\nabla q_2S_2(u, q_2) - F_{x,u}\left( \alpha(x, u) \left( \nabla_x(h_2(u, \tau) + u^Tw_2^1) + \nabla q_2S_2(u, q_2) \right) \right) - \rho_2^{(2)} \left( d_2^{(2)}(x, u) \right)^2 \right) = (-3(1 + \tau) - w_1^1 + x^2(5 + w_1^1), -\tau + 1 - w_2^1 + x^2(1 + w_2^1)) \in Q \setminus \{0\},
\]
for all \( \tau \in [-2, -1], w_1^1 \in E_1, w_2^1 \in E_2 \) and \( x \in \mathbb{R} \). Hence, hypotheses (i) and (ii) of Theorem 5.1 are satisfied. Moreover, \( \mathbb{R}_+^2 \subset K, \mathbb{R}_+^2 = Q \) and
\[
\sum_{i=1}^2 \lambda_i \left\{ \rho_i^{(1)} \left( d_{f_i}^{(1)}(x, u) \right)^2 + \rho_i^{(1)} \left( d_{g_i}^{(1)}(x, u) \right)^2 \right\} + \sum_{j=1}^2 \mu_j \left\{ \rho_j^{(2)} \left( d_{f_j}^{(2)}(x, u) \right)^2 - \tau^Tw_j^2 \right\} = x^2 + 2 + \tau \geq 0.
\]
Thus, suppositions (iii) and (iv) of Theorem 5.1 are also true. Now for point \( \beta_4 \), we get
\[
\left( \eta_1, \eta_2 \right) - \left( \frac{f_1(x) + \Omega(x)C_1}{g_1(x) - \Omega(x)D_1}, \frac{f_2(x) + \Omega(x)C_2}{g_2(x) - \Omega(x)D_2} \right) = \begin{cases} 
(1 - e^{-1}, \frac{6}{13}) \notin K \setminus \{0\} & \text{at } x = 0, \\
(1 - \frac{1}{2}, \frac{7}{19}) \notin K \setminus \{0\} & \text{at } x = 1.
\end{cases}
\]
Hence, the Theorem 5.1 has been verified for \( x = 0, 1 \in S_0 \) and \( \beta_4 \) feasible for (SD).

**Validation of Theorem 5.3:**
For \( \beta_4 \) and \( x = 1 \), the assumptions (ii), (iii) and (iv) hold true (shown above). Moreover,
\[
\left( \eta_1 - \frac{f_1(x) + x^Tv_1^1}{g_1(x) - x^Tv_1^1}, \eta_2 - \frac{f_2(x) + x^Tv_2^1}{g_2(x) - x^Tv_2^1} \right) = \left( \frac{1}{2}, \frac{1}{3} \right) \notin K \setminus \{0\}
\]
which implies that the assumption (i) of Theorem 5.3 also holds. This validates Theorem 5.3. \( \square \)

Next, in the following example, we will discuss the case if the assumption of higher order \( (K \times Q) - (\mathcal{F}, \alpha, \rho, d) \)-type I convexity fails, then the result of Theorem 5.1 may not hold.

**Example 5.5.** Let in the problem (SIFP), \( f : \mathbb{R} \rightarrow \mathbb{R}^2, g : \mathbb{R} \rightarrow \mathbb{R}^2 \), and \( h : \mathbb{R} \times [0, 2] \rightarrow \mathbb{R}^2 \) be given as:
\[
\begin{align*}
 f(x) &= (f_1(x), f_2(x)) = (\sin^2 x, e^x), \\
 g(x) &= (g_1(x), g_2(x)) = ((x + 1)^2, e^x + 1) \text{ and} \\
 h(x, t) &= (h_1(x, t), h_2(x, t)) = (2x - 3t, x + t^2).
\end{align*}
\]
Let the cones be \( K = Q = \{(x, y) \in \mathbb{R}^2 : x \geq 0, y \geq 0\} \) and
\[
\begin{align*}
 G(u, p) &= (G_1(u, p_1), G_2(u, p_2)) = (p_1u^2, -p_2 + 4u), \\
 L(u, p) &= (L_1(u, p_1), L_2(u, p_2)) = (p_1u^2, -p_2 \cos u), \\
 S(u, q) &= (S_1(u, q_1), S_2(u, q_2)) = (q_1 + u + 5, q_2u), \\
 d_{f_1}^{(1)}(x, y) &= d_{g_1}^{(1)}(x, y) = d_{f_2}^{(2)}(x, y) = x(2y - \pi), \text{ and} \\
 d_{f_1}^{(1)}(x, y) &= d_{g_1}^{(1)}(x, y) = d_{f_2}^{(2)}(x, y) = \cos y.
\end{align*}
\]
Further, let $\alpha(x, y) = x^2(4 + y^2)$ and $F_{x,u}(b) = -b(x + u)$. Consider

$$C_1 = [0, 2] = M_2, C_2 = D_2 = E_2 = [-1, 1] \text{ and } D_1 = E_1 = M_1 = [-2, 0].$$

Then, $\Omega(x|C_1) = x + |x|$, $\Omega(x|C_2) = \Omega(x|D_2) = \Omega(x|E_2) = |x|$, $\Omega(t|M_1) = |t| - t$,

$$\Omega(x|D_1) = \Omega(x|E_1) = |x| - x \text{ and } \Omega(t|M_2) = |t| + t.$$ 

Then, the feasible region of the primal problem (SIFP) is $S_0 = \{0\}$ and $\beta_5 = (u, v, w^1, w^2, \lambda, \mu, z, \eta, p, q) = (\frac{\pi}{2}, 1, 1, (-2, 1), (0, 0), (1, 6), (3, 2), (0, -1), (1, 1), (0, 2), (1, 0))$ is feasible for dual problem (SD). For any $\rho^{(1)}_{f_1}, \rho^{(1)}_{f_2}, \rho^{(1)}_{g_1}, \rho^{(1)}_{g_2}, \rho^{(2)}_1, \rho^{(2)}_2 \in \mathbb{R}$, at $\beta_5$,

$$\sum_{i=1}^{2} \lambda_i \left\{ \rho^{(1)}_{f_1}(d^{(1)}_{f_1}(x, u))^2 + \rho^{(1)}_{g_1}(d^{(1)}_{g_1}(x, u))^2 \right\} + \sum_{j=1}^{2} \mu_j \left\{ \rho^{(2)}_j(d^{(2)}_j(x, u))^2 - \tau^T w_j \right\} = 0.$$

Moreover, $K = Q = \mathbb{R}_+^2$. Hence, the assumptions (iii) and (iv) of Theorem 5.1 are satisfied but

$$f_1(x) + x^T z_1 - (f_1(u) + u^T z_1) - G_1(u, p_1) + p_1^T \nabla p_1 G_1(u, p_1) - F_{x,u}(\alpha(x, u) (\nabla_x(f_1(u) + u^T z_1))

+ \nabla_{p_1}(G_1(u, p_1))) - \rho^{(1)}_{f_1}(d^{(1)}_{f_1}(x, u))^2 = \sin^2 x + \frac{\pi^2}{4}(4 + \frac{\pi^2}{4})(x + \frac{\pi}{2})x^2 - 1 < 0, \text{ for } x = 0.$$

Therefore, assumption (i) of Theorem 5.1 does not hold. Moreover,

$$(\eta_1, \eta_2) - \left( \frac{f_1(x) + \Omega(x|C_1)}{g_1(x) - \Omega(x|D_1)} \cdot \frac{f_2(x) + \Omega(x|C_2)}{g_2(x) - \Omega(x|D_2)} \right) = (1, \frac{1}{2}) \in K/\{0\} \text{ at } x = 0.$$ 

Hence, without having the condition of higher order $(K \times Q) - (F, \alpha, \rho, d)$-type $I$ convexity on functions, the result of Theorem 5.1 may not hold. \hfill \square

6. CONCLUSION

To the best of our knowledge, the class of conic non-smooth semi-infinite multiobjective fractional programming problem has not been studied so far. In this article, semi-infinite model with multiple fractional type objective function is formulated. Further, introducing the idea of higher order $(K \times Q) - (F, \alpha, \rho, d)$-type $I$ convex function, the duality relations for Mond-Weir, Wolfe and Schaible type dual models have been developed. Validation of various results obtained have also been shown by demonstrating non trivial examples. Further, it has been shown by giving examples that considering the assumptions of higher order $(K \times Q) - (F, \alpha, \rho, d)$-type $I$ convexity is significant since without this, the duality results obtained may not hold. Exploring optimality relations and duality theorems for (SIFP) over space of symmetric matrices by using $E$-convexity in objective functions be an enthralling future work in this direction.

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