Towards sustainable portfolios: a multi-criteria optimization approach integrating Refinitiv ESG scores

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Abstract

Purpose – As sustainable investing becomes increasingly central to global financial markets, integrating environmental, social, and governance (ESG) criteria into portfolio construction remains a critical challenge for both researchers and practitioners. This study develops and empirically validates a novel tri-objective portfolio optimization framework that simultaneously incorporates financial return, risk management and ESG performance, demonstrating how multi-criteria optimization can effectively balance profitability, volatility and sustainability considerations within a unified decision-making structure.

Design/methodology/approach – A robust tri-objective optimization model combining Pareto efficiency and weighted goal programming is proposed to identify efficient portfolios reflecting trade-offs among return, risk, and ESG performance. The model is applied to standardized ESG scores from Refinitiv Asset4 for 100 international firms over the period 2018–2023. Controlled random portfolio simulations in *R* generate Pareto-optimal solutions, enabling systematic analysis of the interactions between financial and sustainability objectives.

Findings – The results indicate that ESG-prioritized portfolios achieve superior sustainability performance with only a marginal reduction in expected financial returns compared to return-focused portfolios. Balanced portfolios offer an effective compromise, sustaining moderate returns, controlled risk and strong ESG outcomes. Furthermore, ESG integration appears to reduce portfolio volatility, suggesting a stabilizing effect on overall investment performance.

Originality/value – The proposed framework provides investors, portfolio managers, and regulators with a quantitative decision-support tool to reconcile profitability, risk control, and sustainability objectives. By operationalizing ESG integration within a rigorous multi-criteria optimization setting, the study demonstrates that responsible investing can be systematically implemented without materially compromising financial performance, thereby offering both methodological innovation and actionable insights for sustainable finance theory and practice.

Keywords Trade-off, ESG, Multi-criteria optimization, Asset4, Front of pareto, Sustainable portfolios

Paper type Research article

1. Introduction

In recent years, sustainability and ESG (Environmental, Social, and Governance) criteria have become central drivers of investment decision-making, reflecting intensifying concerns about climate change, social responsibility and corporate governance. Investors increasingly expect portfolios to deliver not only competitive risk-return performance but also measurable ESG outcomes.

Traditional portfolio selection models, notably the mean-variance framework, were originally developed without considering ESG dimensions as explicit objectives, creating a persistent gap between financial optimization and sustainability goals (Markowitz, 1952; Amel-Zadeh and Serafeim, 2018).

Recent research has sought to integrate ESG factors into portfolio optimization by extending classical frameworks and implementing multi-criteria decision-making approaches (Fabozzi *et al.*, 2023; Brière and Signori, 2024). These studies highlight the potential of multi-criteria and robust optimization approaches to reconcile financial and societal objectives (Migliorelli, 2023; Gasser *et al.*, 2024).

In this context, the operationalization of sustainability within quantitative portfolio models requires reliable and quantifiable ESG indicators.ESG ratings provide an aggregated assessment of firms' ESG activities and serve as a crucial information source for investors

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seeking responsible investment strategies (Bialkowski and Starks, 2016; Hartzmark and Sussman, 2019; Horn, 2023; Horn and Oehler, 2024). These ratings incorporate numerous ESG indicators; however, significant differences exist among ESG rating providers, reflecting methodological diversity and scope (Berg *et al*., 2022; Chatterji *et al*., 2016; Clementino and Perkins, 2020; Horn and Oehler, 2024; Oehler and Horn, 2025). This variability is noteworthy because ESG ratings are primarily derived from publicly available data, including corporate ESG disclosures and media coverage (Billio *et al*., 2021). Although ESG ratings can be costly, they provide investors with professional assessments from specialized ESG analysts, enhancing decision-making reliability (Oehler and Horn, 2025).

ESG investing, as noted by Agrawal *et al*. (2026), refers to the application of environmental, social, and governance standards in investment decision-making to generate sustainable long-term value. The widespread use of ESG ratings has played a central role in facilitating this shift by translating sustainability dimensions into measurable investment criteria.The growing importance of ESG factors is reshaping portfolio construction and capital allocation toward more responsible and resilient outcomes.

To effectively operationalize ESG criteria within portfolio construction,Operations Research offers a powerful and systematic set of tools for addressing the complex trade-offs inherent in sustainable investing. Unlike traditional financial models that primarily focus on risk or/and return, Operations Research allows for the simultaneous consideration of multiple, potentially conflicting objectives, making it particularly well suited to integrate ESG factors into portfolio selection. Techniques such as multi-criteria optimization, robust decision frameworks, and preference modeling allow for capturing investor heterogeneity, managing uncertainty in ESG ratings, and generating transparent compromise surfaces between financial performance and sustainability outcomes.

While recent studies have applied multi-criteria approaches to ESG portfolio construction (García *et al*., 2024), the full potential of Operations Research methods in this domain remains underexplored. Most existing approaches rely on simplified two-dimensional analyses or incorporate ESG as a secondary constraint, which limits their capacity to capture the complex interactions between sustainability and financial performance in real-world portfolio decisions.

Moreover, the literature still lacks a structured tri-dimensional optimization framework that simultaneously treats return, risk, and ESG performance as equally weighted core objectives within a unified decision architecture. In particular, limited attention has been paid to the explicit integration of standardized ESG scores within a robust multi-criteria Operations Research setting that accounts for investor preference heterogeneity and ESG rating variability. This gap restricts the development of transparent and practically applicable sustainable portfolio construction models.

This study advances the literature by developing a tri-objective optimization framework that incorporates standardized ESG scores from Refinitiv Asset4 and employs empirical simulation in *R* to visualize the compromise among return, risk, and sustainability.

By explicitly accounting for ESG score variability and investor preference heterogeneity, the proposed framework provides a transparent and practical decision-support tool for constructing sustainable and high-performance portfolios in a multidimensional optimization setting.

Given the growing importance of Operations Research in the ESG investing, the paper develops a robust multi-criteria optimization model that explicitly incorporates Asset4 ESG scores to identify portfolios optimally balancing financial return, risk, and ESG performance. Asset4 provides a credible, internationally recognized, and granular measure of sustainability across environmental, social, and governance dimensions, enhancing both reliability and comparability of the results.

In line with this goal, the central research question guiding this study is: How can a multi-criteria optimization approach effectively integrate ESG scores to construct portfolios that simultaneously satisfy investors' financial and sustainability objectives? To address this

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question, the study aims to develop a tri-objective optimization framework incorporating standardized ESG scores, examine the trade-offs between return, risk, and sustainability performance, and provide a practical decision-support tool for investors with heterogeneous sustainability preferences.

Unlike previous studies, our approach emphasizes the explicit integration of standardized ESG scores and provides a practical framework for aligning investment decisions with both economic and sustainability goals. This positioning allows the study to bridge theoretical advances in sustainable finance with practical multi-objective optimization techniques.

This study contributes to the literature on sustainable finance and portfolio optimization in three main ways. First, from a methodological perspective, we develop a tri-objective portfolio optimization framework that simultaneously considers financial return, risk and ESG performance. Unlike traditional approaches that treat ESG criteria as constraints or screening mechanisms, our model integrates ESG performance directly as a core optimization objective and explores the resulting efficiency frontier.

Second, regarding model design and integration, we propose an original framework combining Refinitiv ESG scores with multi-criteria optimization and investor preference modeling. This allows a flexible and transparent representation of sustainability–performance interactions and supports decision-making in a multidimensional portfolio space.

Third, from an empirical and decision-support perspective, we apply the framework to real-world financial data and provide two- and three-dimensional visualizations of the efficient frontier. These tools offer practical insights into how varying sustainability preferences affect portfolio composition and performance, enhancing the model's usefulness for sustainable investment decisions.

The remainder of the paper presents a literature review on ESG, risk and return, followed by methodology, data, empirical results and concluding remarks.

2. Sustainable portfolio construction: literature review on ESG, risk and return

The growing integration of Environmental, Social, and Governance (ESG) factors into financial decision-making has reshaped traditional investment paradigms, leading to the emergence of new frameworks that combine financial performance with sustainability objectives. The following sub-sections outline the conceptual foundations of ESG investing, its relationship with risk and return, and the methodological approaches used to optimize portfolios within this extended framework.

2.1 ESG scores and socially responsible investing

Socially responsible investing (SRI) is a broad approach advocating investment in activities and companies that produce a positive impact on the environment and society (Lauria *et al.*, 2025; Sbaiz, 2023). Traditionally, portfolio construction has relied on the mean-risk framework, formulated by Markowitz in the 1950s, which represents a milestone of modern portfolio theory. In this framework, investors are assumed to be rational and risk-averse, seeking to maximize returns while minimizing risk simultaneously (Markowitz, 1952). However, this model, which focuses solely on financial features, overlooks the growing sensitivity of political institutions, portfolio managers, and new generations of investors toward sustainable development. As a result, integrating ESG factors into portfolio selection has become both a methodological necessity and an empirical challenge, motivating the development of extended frameworks that reconcile financial and non-financial objectives.

Motivated by the increasing popularity of sustainable investments, various approaches have been proposed to incorporate ESG measures into investment decision-making (Bilbao-Terol *et al.*, 2012, 2013; Gasser *et al.*, 2017; Pastor *et al.*, 2021; Steuer and Utz, 2023; Liagkouras *et al.*, 2020; Benedetti *et al.*, 2021). A common strategy extends the traditional mean-variance framework to include ESG considerations, often referred to as the extended

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mean-variance approach (Hirschberger *et al.*, 2013; Gasser *et al.*, 2017; Pedersen *et al.*, 2021). While these studies establish the feasibility of integrating ESG, they often rely on simplified ESG scoring systems and do not fully address uncertainty or investor preference heterogeneity. This observation highlights a gap in existing literature and justifies the choice of a robust multi-criteria optimization framework in the present study.

One of the main challenges of this approach is that it requires investors to provide preference parameters for return, risk, and ESG, which may be subjective and vary across different investor profiles (Varmaz *et al.*, 2022). Despite these challenges, ESG scores have become a widely used tool to quantify environmental, social, and governance performance. Providers such as Refinitiv, MSCI, and Sustainalytics offer granular ESG scores, enabling investors to assess companies not only on financial outcomes but also on their broader societal impact. However, variations among ESG rating providers, as well as differences in data availability and methodological assumptions, introduce inconsistencies that must be carefully addressed in portfolio optimization.

These scores are increasingly employed in portfolio optimization, screening, and reporting, reflecting a growing convergence between sustainable finance and quantitative investment methods.

Overall, while the literature confirms the growing adoption of ESG scores in SRI, there is still a need for methodologies that systematically integrate ESG information, handle uncertainty, and account for diverse investor preferences, thus motivating the methodological choices in this study.

Taken together, these studies suggest that ESG performance may complement traditional financial drivers by providing additional information about firms' long-term stability and operational resilience. This theoretical insight motivates the expectation that higher ESG scores should be associated with competitive or moderately higher portfolio returns, rather than acting as a constraint that penalizes financial performance.

2.2 Return and risk

The mean-variance framework, introduced by Markowitz in 1952, remains a fundamental model in modern portfolio theory, providing a systematic approach to balance expected return and risk (Markowitz, 1952). In this framework, risk is typically quantified as the variance or standard deviation of portfolio returns, reflecting the dispersion of possible outcomes.

Over the years, the model has been extended to address various limitations. Some extensions incorporate higher moments of return distributions to capture asymmetry and tail risks in asset returns (Konno and Yamazaki, 1991). Additionally, robust optimization techniques have been developed to mitigate the impact of estimation errors and model uncertainty, enhancing portfolio resilience (Fabozzi *et al.*, 2007; Tutuncu and Koenig, 2004). However, most extensions still focus primarily on financial metrics, with ESG considerations remaining secondary or exogenous, limiting their applicability in sustainable portfolio construction.

Despite these refinements, the mean-variance approach remains widely used due to its analytical tractability and solid theoretical foundation. Critical reviews of the literature indicate that, although extended mean-variance models can incorporate ESG as an additional constraint or objective, studies vary in how the ESG balance is handled. There is no consensus on the optimal integration strategy, which underscores the importance of developing multi-criteria approaches that simultaneously address return, risk, and ESG within a coherent decision-making framework.

However, the traditional framework focuses solely on financial metrics, which limits its applicability in sustainable investing, where environmental, social and governance factors must also be considered. (Friede *et al.*, 2015; Khan *et al.*, 2016). Investors face challenges when applying the extended mean-variance approach, particularly in defining preference parameters for return, risk and ESG, which may be subjective and vary across profiles

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(Mynbayeva, 2022). These methodological challenges highlight the need for robust and preference-sensitive optimization models that can systematically evaluate ESG trade-offs, forming the basis of this study's methodological contribution.

Integrating ESG considerations into this portfolio selection requires reconciling financial objectives with sustainability goals, creating both challenges and opportunities. A critical review of previous work shows that, although descriptive studies abound, there is a lack of frameworks that combine standardized ESG scores, manage uncertainty, and provide actionable insights for investors, a gap that the present study seeks to fill.

Moreover, the literature consistently highlights the risk-mitigating role of ESG characteristics. Firms with stronger ESG practices tend to exhibit lower volatility, fewer extreme losses, and more stable cash flows, suggesting a negative relationship between ESG performance and portfolio risk. Based on this evidence, we expect higher ESG scores to contribute to reduced downside risk within optimized portfolios.

2.3 Portfolio optimization with ESG

Optimizing an investment portfolio aims to maximize return while minimizing risk, with risk defined as the possibility that the actual return will differ from the expected return, representing the uncertainty of future income (Pekár, 2025).

Integrating ESG considerations extends this framework to balance financial objectives with sustainability goals. The extended mean-variance approach incorporates ESG scores alongside expected return and risk, allowing investors to construct portfolios that are both financially efficient and socially and environmentally responsible (Hirschberger *et al.*, 2013; Gasser *et al.*, 2017; Pedersen *et al.*, 2021). Methodologically, multi-objective optimization techniques enable the identification of portfolios that achieve the best trade-offs among return, risk, and ESG performance (Ben Abdelkader *et al.*, 2020; Hallerbach *et al.*, 2021). Constraint-based models, in turn, enforce ESG thresholds to exclude companies with low sustainability scores or ensure minimum ESG standards within the portfolio (Pedersen *et al.*, 2021; Renneboog *et al.*, 2008).

Recent studies have further advanced these approaches. For example, Papadopoulos and Balta (2022) analyze the compromise between return, risk, and corporate social responsibility using a fuzzy multi-criteria portfolio selection model applied to Dow Jones Industrial Average stocks. They show that portfolios scoring higher on CSR do not necessarily suffer in terms of returns or risk and that extreme CSR scores can correlate with higher portfolio risk. Similarly, García *et al.* (2019) propose a fuzzy multi-objective approach integrating ESG scores as independent fuzzy variables, combined with real-world constraints such as budget and cardinality limits, demonstrating that socially responsible portfolios can outperform benchmarks while satisfying sustainability goals.

Building on these fuzzy multi-criteria approaches, Wang *et al.* (2023) introduce a three-way decisions model based on cumulative prospect theory, which reduces decision risk by creating a boundary region in the decision-making process. Applied to multi-period portfolio selection with fuzzy optimization and particle swarm algorithms, their model outperforms traditional approaches in terms of return, risk, and risk-adjusted measures. Finally, Zhang *et al.* (2023) develop a sustainable portfolio selection approach under an intuitionistic fuzzy framework. Their three-stage methodology evaluates assets ethically, calculates sustainability scores from social, environmental, and economic criteria, and constructs a multi-objective portfolio maximizing return, risk-adjusted performance, and sustainability satisfaction levels.

These studies collectively highlight the increasing sophistication of ESG portfolio optimization models and the importance of handling uncertainty, investor preferences, and multi-dimensional sustainability criteria. Despite these advances, there remains a need for frameworks that combine standardized ESG scores, robust optimization, and preference modeling in a transparent and practical decision support tool, which motivates the present study.

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Building on the recent empirical and methodological advances in ESG portfolio optimization, these studies collectively provide important insights into multi-criteria approaches and fuzzy optimization frameworks. However, a critical analysis reveals several limitations. First, most existing models rely on either simplified scoring systems or specific fuzzy frameworks that may not fully capture the variability and granularity of ESG scores across different providers. Second, they often focus on single-period analyses, limiting their applicability for dynamic, multi-period investment strategies. Third, while investor heterogeneity is recognized, few frameworks explicitly incorporate preference modeling that allows individualized balance between financial and ESG objectives. These gaps highlight the need for a comprehensive, flexible, and empirically validated multi-criteria optimization framework. The present study addresses this by integrating standardized ESG scores, explicitly accounting for score variability, and providing a transparent decision support tool through tri-objective optimization with empirical Pareto front simulations.

Despite these advances, practical challenges remain. Investors must define subjective preference parameters for the relative importance of financial versus ESG objectives, which can vary widely across different investment profiles (Varmaz *et al.*, 2022; Mynbayeva, 2022). Additionally, variations in ESG score methodologies may lead to inconsistent portfolio evaluations (Friede *et al.*, 2015). Nevertheless, the increasing availability of granular ESG data allows portfolio managers to apply more sophisticated optimization models, exploring interaction between financial performance and sustainability outcomes systematically. Overall, integrating ESG into portfolio optimization highlights the convergence of finance and sustainability research, and the growing relevance of multi-criteria decision-making tools in constructing socially responsible investment portfolios.

The reviewed studies also show that incorporating ESG directly into portfolio optimization reshapes the efficient frontier by introducing sustainability-enhancing solutions that remain financially viable. This provides a strong theoretical rationale for expecting ESG-integrated tri-objective optimization to improve the trade-offs between return, risk, and sustainability compared to traditional financial frameworks.

Building on these theoretical insights, the present study derives three testable hypotheses regarding the expected relationships between ESG performance, financial return and portfolio risk within a tri-objective optimization framework:

H1. Higher ESG scores are expected to be associated with competitive expected returns, indicating that sustainability integration does not systematically penalize portfolio performance.

H2. Higher ESG scores contribute to reducing portfolio volatility and downside risk, supporting the role of ESG as a stabilizing factor in portfolio construction.

H3. Integrating ESG into a tri-objective optimization model enhances the identification of efficient trade-offs between return, risk and sustainability compared to traditional financial optimization frameworks.

3. Methodology and data

This section outlines the methodological framework and data used to analyze the integration of ESG criteria into portfolio optimization. The approach combines quantitative modeling with robust financial and sustainability metrics to ensure both theoretical rigor and empirical relevance. Specifically, the methodology proceeds through identifying and describing the data sources and sample selection, defining the ESG and financial variables, constructing the portfolio optimization framework, applying a multi-criteria optimization approach, performing robustness and sensitivity analyses, validating the empirical results and highlighting the methodological contribution of the study.

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3.1 Data source and sample selection

This study employs ESG data from Refinitiv Asset4 (formerly Thomson Reuters Asset4), one of the most extensively used and academically validated databases for assessing firms' sustainability performance. Asset4 provides standardized, comparable, and methodologically transparent ESG scores for a global universe of publicly listed firms. The database compiles information from objective and publicly available sources, including annual reports, sustainability disclosures, company websites, and reputable publications and processes them through a scoring system designed to ensure consistency, replicability and cross-country comparability.

Recent studies underscore its academic reliability and adoption, as Refinitiv data have been widely employed in ESG social sciences research to examine corporate performance, investment behavior, and risk return dynamics (Broadstock *et al*., 2021; Sokolov, 2023; Blancard and Petit, 2024).

Our empirical sample comprises 100 publicly listed firms observed over the 2018–2023 period. The selection was based on three key considerations: the continuous availability of ESG data throughout the six years to ensure temporal consistency, inclusion of firms from diverse sectors to reflect heterogeneity in ESG practices and financial performance and a focus on companies operating in global markets to enhance representativeness. To ensure data reliability, all ESG scores and financial variables were cross-checked for completeness, consistency absence of outliers, and firms with missing or inconsistent data were excluded from the sample.

The choice of the 2018–2023 period is further motivated by methodological considerations related to ESG data quality. ESG reporting practices underwent significant harmonization after 2017, and Refinitiv revised several components of its scoring methodology to enhance stability and comparability across firms and regions (Berg *et al*., 2022; Broadstock *et al*., 2021). Using a post 2018 window therefore ensures that the ESG scores are methodologically consistent over time, avoiding structural breaks that could bias longer-horizon analyses. Although a longer period could capture delayed impacts such as ESG controversies, recent literature emphasizes that shorter but methodologically stable windows are preferable for isolating the true relationship between ESG performance, risk, and return (Friede *et al*., 2015; Pástor *et al*., 2021). The selected horizon thus balances temporal representativeness with data reliability.

3.2 Variables

The ESG dimension is captured using the global ESG score from Asset4, which aggregates environmental, social, and governance indicators. This composite score is constructed using Refinitiv's proprietary weighting methodology, ensuring comparability across firms, sectors and countries. Each dimension is also available separately, but for the baseline analysis we focus on the composite ESG score to reflect the overall sustainability profile of each firm. The use of the aggregated ESG score is theoretically consistent with a holistic view of corporate sustainability and is commonly adopted in ESG portfolio optimization studies.

In addition to ESG data, financial information is extracted from Refinitiv, which provides stock returns, market capitalization and accounting variables. The combination of ESG and financial data ensures that both sustainability and performance considerations are integrated into portfolio construction. This integrated dataset allows us to align the empirical design with the theoretical framework of multi-criteria decision-making, where financial and non-financial objectives are jointly optimized.

Specifically, for each firm i in year t, we compute:

(1) Expected return: average historical return over the estimation window, calculated using continuously compounded returns to ensure consistency across assets.

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(2) Risk: variance-covariance structure of returns across the sample, used to compute portfolio volatility, thereby capturing both individual asset risk and cross-asset correlations.

(3) ESG score: standardized value from Asset4, rescaled to ensure compatibility with the financial variables within the optimization framework.

The choice of variables follows established standards in the sustainable finance literature. Expected return and downside risk (captured through variance or CVaR) are the most widely used financial metrics in multi-objective portfolio optimization, as they jointly reflect performance and exposure to extreme losses (Fabozzi *et al*., 2007; Pedersen *et al*., 2021). The use of Refinitiv ESG scores is also well supported by prior studies due to their transparency, global coverage and methodological consistency, making them one of the preferred measures for empirical research on ESG–performance relationships (Friede *et al*., 2015). Including these three dimensions aligns the study with recognized methodological practices and ensures that the model captures the essential trade-offs documented in the literature. Furthermore, the objective of this study is to examine structural trade-offs within portfolio optimization rather than event-driven market reactions. As such, the selected time window is sufficient to capture cross-sectional relationships between ESG performance, risk and return.

This dual dataset allows us to operationalize the integration of ESG into a portfolio optimization framework. To enhance transparency and methodological rigor, all variables are subjected to systematic consistency checks, outlier detection procedures, and normalization techniques. In addition, alternative variable specifications and normalization schemes are examined as part of the sensitivity and robustness analyses, ensuring that the results are not driven by specific measurement choices.

3.3 Portfolio optimization framework: mathematical formulation

Portfolio optimization lies at the heart of investment decision-making, traditionally aiming to balance expected return and risk. This risk–return compromise constitutes the theoretical foundation of modern portfolio theory and provides the baseline upon which ESG considerations are integrated in this study.

To enhance robustness, we adopt a tri-objective optimization framework based on multi-criteria decision-making principles. This approach is particularly suited to handling conflicting objectives such as return, risk, and ESG performance. Investor heterogeneity is incorporated through sensitivity analyses on preference weights, allowing systematic exploration of portfolio outcomes across different preference structures.

Portfolio risk can be mitigated through diversification, whereby asset exposures are distributed across multiple securities to reduce overall volatility. Building on this classical principle, integrating sustainability objectives into portfolio optimization requires the explicit inclusion of ESG criteria within the traditional Markowitz framework. By extending the risk–return model to incorporate ESG performance as a third optimization objective rather than a secondary constraint, the framework ensures conceptual consistency with sustainability-oriented investment strategies.

In this context, additional constraints can be applied to the ESG scores or to the individual environmental (E), social (S), and governance (G) components (Xidonas and Essner, 2024; De Spiegeleer *et al*., 2023; Cesarone *et al*., 2022; Torricelli and Bertelli, 2022).

This section outlines the development of a mathematical programming model that integrating expected return, the risk measure, and ESG indicators. First, we define the model's variables and the parameters used in its formulation.

Integrating ESG performance alongside traditional financial criteria inevitably introduces conflicts between objectives. A portfolio that maximizes ESG performance may not simultaneously maximize returns, and a portfolio that minimizes risk may score relatively lower on ESG measures. To explicitly capture and analyze these conflicts, this study adopts a

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multi-criteria optimization framework combining combining efficiency frontier analysis and preference-based scalarization.

To explicitly address these interactions, this study combines two complementary approaches.

(1) **Efficiency Frontier:** We identify the set of optimal portfolios, where no objective can be improved without deteriorating another. The resulting frontier represents all efficient trade-offs among return, risk, and ESG performance and serves as a validation benchmark ensuring that retained solutions are non-dominated across all criteria.

(2) **Weighted Goal Programming:** To reflect heterogeneous investor preferences, we introduce a scalarized utility function defined as:

$$U(w) = \alpha\,\mathrm{R}(w) - \beta\sigma^2(w) + \gamma\,\mathrm{ESG}(w)$$

where $\alpha, \beta, \gamma \geq 0$, represent the relative importance assigned to return, risk, and ESG performance, respectively.

A structured sensitivity analysis is conducted by systematically varying these weights over predefined grids, allowing us to assess the stability of portfolio compositions and performance rankings across preference profiles.

By adjusting these parameters, the framework can simulate various types of investors, including those focused on ESG performance, those with a low tolerance for risk, and those seeking to maximize returns, and can then determine the corresponding portfolio configurations.

Before introducing the mathematical models, we first present the following notation framework:

3.3.1 Notations. n: Number of available assets.

$x = (x_1, x_2, ..., x_n)^T$: Portfolio weight vector (decision variable), where x_i represents the proportion of capital invested in asset (*1*), with:

$$\sum_{i=1}^{n} x_i = 1, \mathrm{x}_i \geq 0\,\forall i$$

$r = (r_1, r_2, ..., r_n)^T$: Vector of expected returns of the assets.

$\sum \in R^{n\times n}$: Covariance matrix (symmetric and positive definite) of asset returns.

$s = (s_1, s_2, ..., s_n)^T$: Vector of ESG (Environmental, Social, and Governance) scores.

1: Column vector of dimension (n) whose components are all equal to 1.

χ: Feasible set of constraints.

$$\chi = x \in R \text{ and } \sum_{i=1}^{n} x_i = 1, \mathrm{x}_i \geq 0\,\forall i$$

$W = (w_1, w_2, w_3)$: Vector of weighting coefficients assigned respectively to the criteria of return, risk, and ESG performance.

$\mathrm{ESG}_{\min}$: Desired minimum level for the portfolio's ESG score (optional).

$l, \mathrm{u} \in R^n$: Lower and upper bounds on (x) (optional).

3.3.2 Criteria. The optimization problem involves three objective functions (to be maximized or minimized depending on the convention):

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(1) Expected Return (*to maximize*)

$f_1(x) = \mu(x) = \sum_{i=1}^{n} r_i x_i = r^T x$, where ($r_i$) is the expected return of asset (1).

(2) Risk (*to minimize*)

We consider the portfolio variance (or equivalently, its standard deviation):

$f_2(x) = \sigma^2(x) = x^T \sum x$. where ($\sum$)) is the covariance matrix of asset returns. Alternatively, the standard deviation $\sigma(x) = \sqrt{x^T \sum x}$ can be used.

(3) ESG Performance (*to maximize*)

Portfolio ESG score :

$f_3(x) = \sum_{i=1}^{n} \text{ESG}_i x_i = \text{ESG}^T x = \sum_{i=1}^{n} s_i x_i = s^T x$.Where ($s_i = \text{ESG}_i$)is the ESG (Environmental, Social, and Governance) score of assets (*1*).

We note that the units of the three criteria differ $f_1(x), f_2(x), f_3(x)$, which makes normalization often necessary for proper scalarization. Min–max normalization is applied to each criterion prior to aggregation, ensuring comparability and preventing dominance driven by scale effects.

3.3.3 Tri-objective formulation.

$$\max f_1(x) = r^T x \text{ (Return)}$$
$$\min f_2(x) = x^T \sum x \text{ (Risk)}$$
$$\max f_3(x) = \text{ESG}^T x \text{ (ESG Performance)}$$
$$s.\text{c} \sum_{i=1}^{n} x_i = 1, \text{x}_i \geq 0 \, \forall i$$

We seek the set of vectors $x \in \chi$ that simultaneously optimize the triplet of objective functions$(f_1(x), -f_2(x), f_3(x))$ we take$(-f_2(x))$. If we aim to express the problem as a maximization problem, we can write:

$$\underset{x \in \chi}{\text{Max}} F(x) = (f_1(x), -f_2(x), f_3(x))$$
$$\text{with} \chi = \{x \in R^n |$$
$$\underset{x \in \chi}{\text{Max}} F(x) = [f_1(x)|][-f_2(x)|]$$

In general, the solution is not unique, therefore, we focus on non-dominated solutions. Given the absence of a single global optimum, the analysis emphasizes identifying and characterizing these solutions, which define the efficiency frontier of the decision space.

3.3.4 Solution method.

(1) Weighted Sum

After normalization, we maximize: $\underset{x \in \chi}{\text{Max}} W(x) = \lambda_1 \widetilde{f}_1(x) + \lambda_2 \widetilde{f}_2(x) + \lambda_3 \widetilde{f}_3(x)$, where $\widetilde{f}_i(x)$ the normalized objectives et $\widetilde{f}_2(x) = -\widetilde{f}_2(x)$ (A converting risk into a criterion to be maximized) and$\lambda_i \geq 0, \lambda_i = 1$

(2) Constraints

We optimize a primary criterion while imposing bounds on the others:

$$\underset{x \in \chi}{\text{Max}} r^T x$$

$$\left\{ x^T \sum x \leq \overline{\sigma}^2 \right|$$

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By varying $\overline{\sigma}^2$ and $\underline{S}$ the bounds, we obtain the Pareto front.

(3) Goal Programming

Minimize the distance to the ideal vector $Z = (f_1^{\max}(x), -f_2^{\min}(x), f_3^{\max}(x)) \min_{x\in\chi} \max_{i=1,2,3} W_i$ $|\widetilde{f}_i(x) - Z_i|$ Good for reflecting robust preferences.

(4) Robust Approach (If the parameters are uncertain $r, \sum, s$) if $r$and/or s are uncertain, we can formulate a robust problem, for example:

$\max_{x\in\chi} \min_{(r,s)\in U} \lambda_1 \widetilde{r}x^T + \lambda_3 \widetilde{s}x^T - \lambda_2 x^T \sum x$, where U is an uncertainty set.

At this stage, we can also present the usual Constraints:

Budget: $\sum_{i=1}^{n} x_i = 1, x_i \geq 0$
Bounds: $l_i \leq x_i \leq u_i$
Average ESG threshold: $s^T x \geq s_{\min}$
Cardinality (at most k assets): $y_i \leq k$
Mixed-integer model: $x_i \leq y_i.u_i, y_i \in \{0, 1\}$
As for normalization, before combining the objectives, we normalize:

$$\widetilde{f}_1(x) = \frac{rx^T - f_1^{\min}}{f_1^{\max} - f_1^{\min}}$$

$$\widetilde{f}_2(x) = \frac{x^T \sum x - f_2^{\min}}{f_2^{\max} - f_2^{\min}}$$

$$\widetilde{f}_3(x) = \frac{sx^T - f_3^{\min}}{f_3^{\max} - f_3^{\min}}$$

Then we use $\widetilde{f}_2(x) = -\widetilde{f}_2(x)$ if we want to maximize all criteria.

In this section, we implement a numerical simulation in R aimed at approximating the efficiency frontier associated with a portfolio optimization problem. The simulation approach is chosen to address potential non-convexities and high dimensionality, which may limit the applicability of closed optimization techniques.

The adopted approach is based on a methodology of random generation of a large number of feasible portfolios, each characterized by a vector of weights ($x = (x_1, x_2, ..., x_n)$) satisfying the budget constraint ($\sum_{i=1}^{n} x_i = 1, x_i \geq 0$).

To ensure robustness, the simulation is repeated across multiple random seeds and convergence is assessed by examining the stability of the resulting efficient solutions.

For each simulated portfolio, the three key indicators are computed:

(1) the expected return ($f_1(x) = \sum_{i=1}^{n} r_i x_i$),

(2) the risk ($f_2(x) = \sigma(x) = \sqrt{x^T \sum x}$),

(3) and the aggregated ESG performance ($f_3(x) = \sum_{i=1}^{n} \text{ESG}_i x_i = \sum_{i=1}^{n} s_i x_i$),

Where (r_i), ($\sum$) et ($\text{ESG}_i = s_i$) respectively denote the expected return, the covariance matrix, and the ESG score of asset (i).

The generated portfolios are evaluated across the three criteria to identify non-dominated solutions, forming the multi-dimensional efficiency frontier. This frontier provides a

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comprehensive view of interactions between financial return, risk, and ESG performance. Robustness and stability are ensured by repeating simulations under different random seeds and performing sensitivity analyses on preference weights and normalization schemes. This procedure offers a reliable empirical approximation of the efficiency frontier, particularly in high-dimensional or non-convex contexts, and serves as an internal validation of the proposed framework.

4. Pareto Front simulation of a tri-criteria portfolio via random generation approach

This section presents the methodological approach adopted for the numerical simulation of a tri-objective investment portfolio, simultaneously integrating the dimensions of financial return, risk and ESG performance.

The main goal is to empirically approximate the efficiency frontier, representing portfolios for which no other combination of assets can simultaneously improve all criteria.The proposed approach relies on a controlled random generation of feasible portfolios, subject to the standard budget and non-negativity constraints, followed by a multi-objective filtering process based on dominance. This filtering identifies the non-dominated portfolio configurations, corresponding to the most efficient compromises among expected return, risk level and overall ESG score.

Such a strategy enables the characterization of the tri-criteria efficiency frontier provides an empirical visualization of the interactions between financial and extra financial objectives within an integrated decision making framework.

To ensure empirical rigor and reproducibility, the simulation procedure is repeated across multiple independent runs, allowing the assessment of the stability and robustness of the resulting Pareto front. The number of simulated portfolios and random seeds are kept consistent across experiments to guarantee comparability of results.

4.1 Simulation of the Portfolio's basic data

In the first stage, an investment universe composed of (n) financial assets is simulated. Each asset is defined by three fundamental parameters:

(1) the expected return (r_i), representing the anticipated financial performance of asset (i);

(2) the individual volatility and cross-correlations among assets, grouped within a symmetric covariance matrix $(\sum)$, reflecting the dependency structure between returns;

(3) the ESG score ($\text{ESG}_i = s_i$), normalized within the interval ([0,1]), which captures the non financial performance of each asset across the environmental, social, and governance dimensions.

These three components form the informational basis for assessing the multi-dimensional performance of portfolios.

The simulation of such data aims to reproduce a realistic market environment, in which assets exhibit heterogeneous levels of return, risk, and sustainability. This heterogeneity is essential to ensure a credible analysis of trade-offs between financial performance and ESG criteria, and to enable the empirical construction of a meaningful multi objective frontier.

To validate the realism of the simulated data, summary statistics of returns, risk, and ESG scores are compared with the empirical distributions observed in the original dataset. This step ensures that the simulated investment universe adequately reflects the heterogeneity and scale of real-world financial and sustainability characteristics.

4.2 Random generation of candidate portfolios

In this second stage, many random portfolios are generated in order to explore the space of possible asset combinations.

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Each portfolio is represented by a vector of weights $x = (x_1, x_2, \ldots, x_n)$, where each ($x_i$) denotes the proportion of capital invested in asset (i).

The weights are normalized to satisfy the following budget constraint:

$$\sum_{i=1}^{n} x_i = 1, \mathrm{x}_i \geq 0, \forall i$$

which ensures that all generated portfolios are feasible and adhere to standard investment constraints, namely full capital allocation and the prohibition of short-selling.

A large number of candidate portfolios ($N \geq 50{,}000$) is generated in each simulation run to ensure sufficient coverage of the feasible space. To assess robustness, the simulation is replicated using different random seeds, and the resulting Pareto fronts are compared in terms of shape, dispersion, and dominance structure.

This strategy of controlled random generation allows for a uniform and unbiased exploration of the search space, ensuring a diverse set of portfolio configurations for subsequent multi-objective analysis.

4.3 Computation of the three performance criteria

For each generated portfolio, the three fundamental dimensions of performance are systematically evaluated:

(1) **Expected Return**, defined as the weighted average of the expected returns of the assets composing the portfolio:

$$f_1(x) = \sum_{i=1}^{n} r_i x_i = r^T x$$

(2) **Overall Risk**, measured by the portfolio's volatility, computed from the covariance matrix of asset returns:

$$f_2(x) = \sigma(x) = \sqrt{x^T \sum x}$$

(3) **Aggregated ESG Score**, representing the portfolio's societal performance, obtained through a linear combination of the individual ESG scores:

$$f_3(x) = \sum_{i=1}^{n} \mathrm{ESG}_i x_i = \mathrm{ESG}^T x = \sum_{i=1}^{n} s_i x_i = s^T x$$

These three measures allow each portfolio to be associated with a performance triplet $(f_1(x), f_2(x), f_3(x))$, which defines its position in the three-dimensional objective space.

The collection of all such points forms a cloud of feasible solutions representing the boundary of the most efficient portfolios in the multi-objective sense.

All performance criteria are normalized prior to multi-objective evaluation to ensure scale comparability. As a robustness check, alternative normalization schemes (min–max normalization and z-score standardization) are applied, and the resulting portfolio rankings are compared to verify consistency.

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4.4 Identification of pareto-optimal portfolios

Once all simulated portfolios have been evaluated according to the three performance criteria, the next step consists in identifying the solutions belonging to the Pareto front. In fact, a portfolio (*A*) is said to be dominated by another portfolio (B) if and only if the following three conditions are satisfied:

$$\{f_1(B) \geq f_1(A), |\{f_2(B) \leq f_2(A), |$$

In other words, portfolio (B) provides a higher expected return and/or ESG score, while maintaining an equal or lower level of risk.

Portfolios that are not dominated by any other alternatives constitute the set of efficient solutions.

The resulting efficiency frontier summarizes the best attainable compromises among return, risk, and sustainability, reflecting the coexistence of multiple optimal portfolios aligned with different investor preferences. The robustness of this frontier is assessed by analyzing the stability of efficient portfolios across simulation runs. A high degree of consistency in their composition and distribution indicates that the results are structurally reliable rather than driven by random sampling effects.

4.5 Visualization of the three-dimensional Pareto Front

The final step of the methodology consists in visualizing the Pareto front in three-dimensional space, using interactive graphical tools such as the Plotly library in *R*.

This visual representation provides an intuitive way to examine the multi-criteria relationships, allowing one to directly observe how prioritizing sustainability or higher returns affects the overall risk level.

The proposed methodology combines random generation, multi-criteria evaluation, and filtering to produce an empirical approximation. It offers a powerful exploratory tool for analyzing the interplay between return, risk, and ESG performance, and serves as a methodological prelude to the subsequent implementation of more sophisticated multi-objective optimization techniques.

To support validation, the three-dimensional visualization is complemented by two-dimensional projections and density plots, which allow for cross-verification of relationships between pairs of objectives. Consistent patterns across these visualizations confirm the robustness of the identified efficiency frontier and reinforce the interpretability of the results.

5. Results and discussion

This section presents and discusses the main empirical findings of the study. The results are structured in several stages to ensure clarity and analytical coherence. First, a descriptive analysis of the data is conducted to provide a general overview of the statistical properties and correlations among the key variables. Then, the outcomes of the heuristic portfolio simulations are examined to highlight the trade-offs between financial performance (return), risk and ESG performance.

5.1 Descriptive statistics and correlation analysis

Before presenting the optimization outcomes, it is essential to describe the main characteristics of the dataset used in this study. Table 1 reports the descriptive statistics of the key variables, namely returns, volatility and ESG scores, for the 100 firms included in the sample over the 2018–2023 period. These summary statistics provide an overview of the distribution, variability and range of each variable, serving as a foundation for the subsequent portfolio analysis. Examining these descriptive metrics helps to identify general trends in firm performance and sustainability profiles, as well as to assess the level of heterogeneity across companies and industries.

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Table 1. Descriptive statistics of returns, risk and ESG (2018–2023)

Variable	Mean	Std. Dev	Min	Max	N
Return (%)	7.85	12.30	−18.5	32.7	600
Volatility (risk)	15.20	5.10	6.2	28.4	600
ESG Score	64.50	12.80	32	92	600

The average annual return over the period is approximately 7.85%, with substantial variation (standard deviation of 12.3%), indicating considerable heterogeneity in firm performance. Portfolio risk (volatility) averages 15.2%, reflecting a moderate risk level across firms. The mean ESG score is 64.5, suggesting that most firms in the sample maintain intermediate levels of sustainability performance, although the wide dispersion (standard deviation of 12.8) reveals significant diversity in ESG practices.

This dispersion is particularly relevant for portfolio construction, as it implies meaningful opportunities for cross-sectional selection and diversification. The coexistence of firms with similar returns but markedly different ESG scores, as well as firms with comparable ESG performance but distinct risk profiles, suggests that sustainability characteristics may provide an additional dimension for differentiating assets beyond traditional financial metrics. Such heterogeneity is a necessary condition for ESG portfolio optimization to generate non-trivial compromise solution between return, risk and sustainability objectives.

To further explore the relationships among the key variables, Table 2 presents the correlation matrix between returns, portfolio risk and ESG scores. These correlation coefficients provide initial insights into how financial performance, risk exposure and sustainability measures are interrelated.

The results reveal a positive correlation between ESG scores and return (0.28), suggesting that firms with higher sustainability performance tend to achieve higher financial returns. Meanwhile, the negative correlation between ESG and risk (−0.30) indicates that portfolios integrating ESG criteria may benefit from reduced volatility.

These correlations suggest that ESG characteristics may act as a partial risk-mitigating factor rather than a pure return-enhancing mechanism. The negative association between ESG scores and volatility is consistent with the view that firms with stronger sustainability practices exhibit more stable cash flows, better governance structures and lower exposure to regulatory or reputational risks. This risk-reduction channel is particularly relevant for risk-averse investors, for whom improved ESG performance may enhance portfolio efficiency by lowering downside risk without necessarily sacrificing expected returns.

Furthermore, the moderate magnitude of the ESG–return correlation indicates that sustainability performance is unlikely to dominate financial outcomes on its own, but instead complements traditional financial drivers. This finding supports the interpretation that ESG integration can improve risk performance rather than guaranteeing superior raw returns, thereby aligning with modern portfolio theory where investors seek to optimize trade-offs rather than maximize a single objective.

This evidence highlights the potential compatibility between financial and non financial objectives, providing a theoretical rationale for ESG integration in investment strategies.

Table 2. Correlation matrix between ESG, return, and risk

Variable	Return	Risk	ESG score
Return	1.00	−0.45	0.28
Risk	−0.45	1.00	−0.30
ESG Score	0.28	−0.30	1.00

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Overall, the descriptive and correlation analyses provide early empirical support for the tri-criteria portfolio framework adopted in this study. By demonstrating that ESG scores are simultaneously related to both return and risk, these preliminary results justify the subsequent use of multi-objective optimization techniques to explore how investors can balance financial performance and sustainability considerations in practice.

These descriptive relationships are broadly consistent with prior empirical findings in the sustainable finance literature. Friede *et al.* (2015) document in their meta-analysis that the majority of studies report either a neutral or positive ESG–return association, which aligns with our observed positive correlation between ESG scores and returns. This convergence supports the view that ESG integration does not penalize financial performance.

Similarly, Khan *et al*. (2016) show that firms investing in material sustainability issues exhibit superior risk-adjusted performance, while Broadstock *et al*. (2021) find that stronger ESG performance contributes to greater resilience during market stress. Our finding of a negative ESG–risk correlation reinforces this risk mitigation channel.

However, unlike studies suggesting that ESG effects may materialize only over longer horizons, our results indicate that even within a relatively recent and stable period (2018–2023), ESG performance is already associated with lower downside risk. This suggests that the risk-reduction benefits of ESG may operate more immediately through improved governance quality, enhanced stakeholder trust, and reduced exposure to operational or reputational shocks.

Overall, our findings converge with the dominant empirical evidence supporting a risk-based explanation of ESG value creation, while contributing additional support from a portfolio optimization perspective.

5.2 Portfolio optimization outcomes

The following results summarize the outcomes of the tri-objective portfolio optimization model under four distinct investor preference scenarios, reflecting varying priorities among expected return, risk (measured by CVaR) and ESG performance.

Table 3 reports representative portfolios selected from the efficient set, each illustrating a specific investment orientation.

The return-maximizing portfolio achieves the highest expected return (11.5%) but is associated with the highest level of risk (19.8%) and the lowest ESG score (55). From a financial perspective, this outcome is consistent with traditional risk–return theory, where superior returns are obtained by accepting higher exposure to downside risk. The relatively weak ESG profile of this portfolio suggests a concentration in firms with lower sustainability standards, which may offer short-term performance advantages but expose investors to higher long-term risks related to regulatory pressure, governance failures or reputational damage.

In contrast, the risk-averse portfolio delivers the lowest risk level (9.5%) and a more modest return (6.7%), while exhibiting a higher ESG score (63). This configuration reflects a defensive investment strategy focused on capital preservation and downside risk control. The higher ESG performance of this portfolio supports the view that sustainability-oriented firms tend to exhibit more stable cash flows and lower exposure to extreme losses, reinforcing the

Table 3. Optimization results under different investor preferences

Preference type	Return (%)	Risk (%)	ESG score	Portfolio notes
Return-maximizing	11.5	19.8	55	Focus on high-return assets
Risk-averse	6.7	9.5	63	Balanced low-risk portfolio
ESG-prioritizing	7.2	13.0	82	High ESG exposure, moderate return
Balanced ($\alpha = \beta = \gamma$)	8.9	14.1	70	*Compromise solution*

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role of ESG characteristics as a complementary risk-mitigation mechanism rather than a pure return-enhancing factor.

The ESG-prioritizing portfolio reaches a markedly high ESG score (82) while maintaining an intermediate level of risk (13.0%) and a competitive return (7.2%). Importantly, although this portfolio does not maximize financial returns, the observed performance remains comparable to that of the risk-averse strategy. This finding challenges the assumption of a strict trade-off between sustainability and profitability and suggests that strong ESG integration can be achieved without a disproportionate sacrifice in expected returns, particularly for long-term investors.

Finally, the balanced portfolio, which assigns equal importance to return, risk, and ESG objectives ($\alpha = \beta = \gamma$), represents a pragmatic compromise solution. With an expected return of 8.9%, moderate risk (14.1%), and a solid ESG score (70), this portfolio illustrates how multi-objective optimization can generate well-diversified investment strategies that jointly satisfy financial efficiency and sustainability considerations. From a practical standpoint, this solution is particularly relevant for institutional investors facing both performance constraints and ESG mandates.

Overall, these results demonstrate that tri-objective portfolio optimization does not yield a single optimal solution but rather a spectrum of efficient portfolios aligned with different investor preferences. By explicitly mapping the relationship between return, risk and ESG performance, the proposed framework provides actionable insights for investors seeking to incorporate sustainability into portfolio decisions while maintaining financial discipline.

These results are consistent with prior empirical evidence showing that ESG-integrated portfolios tend to exhibit lower downside risk while maintaining competitive returns (Pedersen *et al*., 2021; García *et al*., 2019). The performance of the ESG-prioritizing portfolio aligns with findings from Papadopoulos and Balta (2022), who highlight that portfolios scoring high on ESG or CSR dimensions can achieve financial efficiency comparable to traditional portfolios. Conversely, the behavior of the return-maximizing portfolio reflects the classical risk–return trade-off observed in standard financial models, confirming that aggressive return-seeking strategies often imply lower ESG exposure, as also noted in Hallerbach *et al.* (2021).

5.3 Visualization of the Pareto front

The tri-criteria optimization generated a efficient portfolios, balancing expected return, risk and ESG performance. Three representative portfolios were selected to illustrate key balance, namely, maximum return (highest expected return), minimum risk (lowest volatility) and maximum ESG (highest ESG exposure).

Figure 1 presents the 3D Pareto front (Return / Risk / ESG). Gray points represent all optimal portfolios, while colored diamonds indicate the selected representative portfolios, blue for Max Return, green for Min Risk and orange for Max ESG.

To enhance interpretability, Figure 2 provides three successive views of the Pareto front, each emphasizing one representative portfolio. These visualizations allow for a clearer assessment of the relative position of each optimal solution within the efficient surface and facilitate an economic interpretation of the trade-offs embedded in the tri-objective optimization problem.

Beyond visual inspection, the Pareto front provides economically meaningful insights into how financial performance, risk exposure and sustainability objectives interact. The Maximum Return portfolio (blue) occupies a region characterized by high expected returns but also elevated volatility and only moderate ESG exposure. This confirms the classical risk–return compromise and indicates that aggressive return-seeking strategies may limit sustainability outcomes.

In contrast, the Maximum ESG portfolio (orange) achieves substantially higher ESG scores while maintaining moderate risk levels and only a limited reduction in expected return. This

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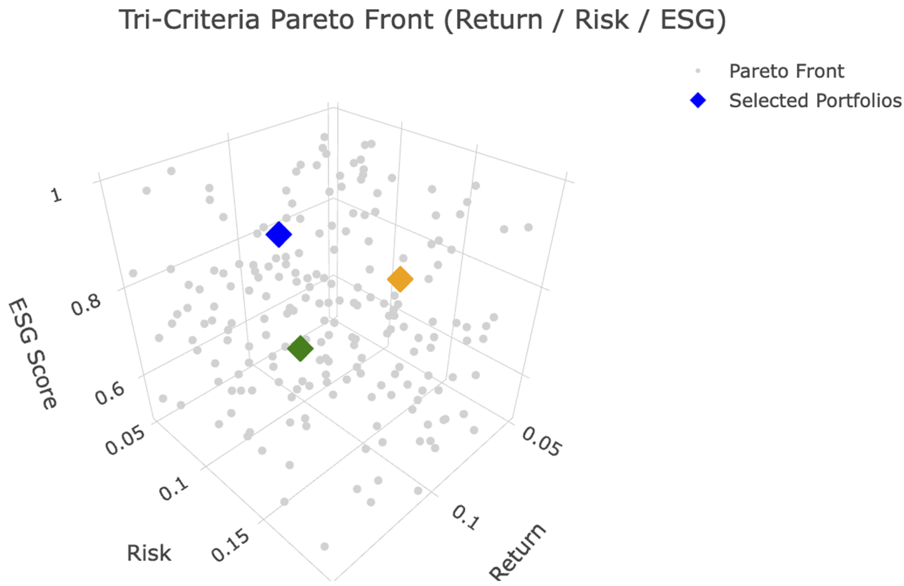

Figure 1. 3D Pareto front of simulated portfolios

result suggests that prioritizing sustainability does not necessarily imply a severe financial penalty, but rather a marginal concession in returns in exchange for significantly improved ESG performance.

The Minimum Risk portfolio (green) illustrates the stabilizing role of diversification and ESG integration. It combines low volatility with above-average ESG scores and acceptable returns, highlighting that risk-averse investors can simultaneously achieve downside protection and sustainability objectives.

The three-dimensional visualization exhibits a convex shape, reflecting a continuous spectrum of efficient interaction among return, risk and ESG performance. This structure implies that no single portfolio dominates others across all criteria and that investor preferences play a crucial role in portfolio selection. Balanced portfolios, located near the center of the Pareto surface, offer a compromise solution that aligns moderate financial performance with meaningful sustainability outcomes, making them particularly relevant for institutional and socially responsible investors.

To further explore the relationships among portfolio objectives, Figures 3–5 present the 2D projections of the optimal portfolios. The Return vs Risk projection illustrates the classical efficiency frontier, emphasizing the balance between expected return and portfolio volatility. The Return vs ESG projection depicts the connection between financial performance and sustainability, showing how higher returns may correspond to moderate ESG scores, while maximizing ESG can entail slightly lower returns. Finally, the Risk vs ESG projection highlights portfolios that achieve sustainable performance with controlled risk, providing insights into the interaction between volatility and ESG exposure. These projections complement the 3D Pareto front by offering clear, interpretable views of the multi-criteria optimization outcomes, facilitating informed investment decisions.

The structure of our Pareto front is consistent with the findings of Hallerbach *et al.* (2021), who demonstrate that including ESG as an explicit optimization objective expands the efficient frontier by generating new compromise solutions. Similarly, Zhang *et al.* (2023) report that multi-criteria approaches integrating sustainability dimensions tend to produce portfolios with more balanced profiles across financial and ESG criteria. The behavior of our

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Figure 2. Three views of the 3D Pareto front of simulated portfolios

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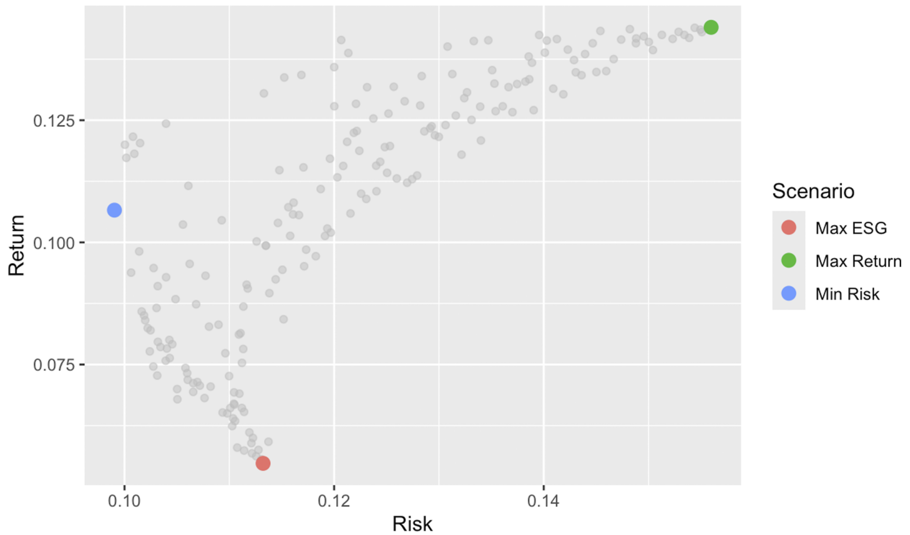

Figure 3. Return vs risk projection

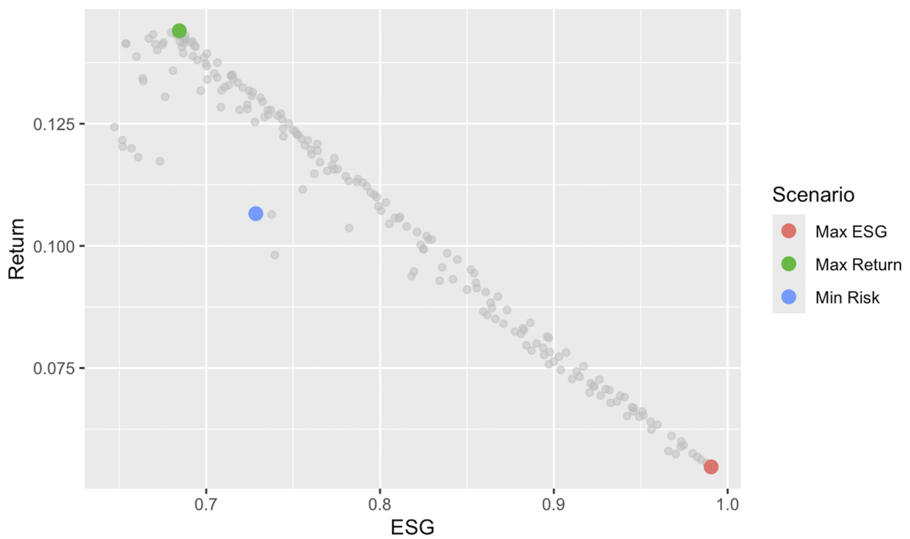

Figure 4. Return vs ESG projection

maximum ESG and minimum risk portfolios aligns closely with these studies, reinforcing the conclusion that ESG integration reshapes feasible portfolio configurations without unduly compromising financial performance.

The Return–Risk projection (Figure 3) confirms the traditional efficient frontier, where higher expected returns are associated with higher volatility, consistent with the classical Markowitz mean–variance framework. Portfolios with stronger ESG profiles tend to lie closer to the lower-risk region for comparable return levels, suggesting that ESG integration may contribute to improved risk-adjusted performance. This pattern can be explained by the

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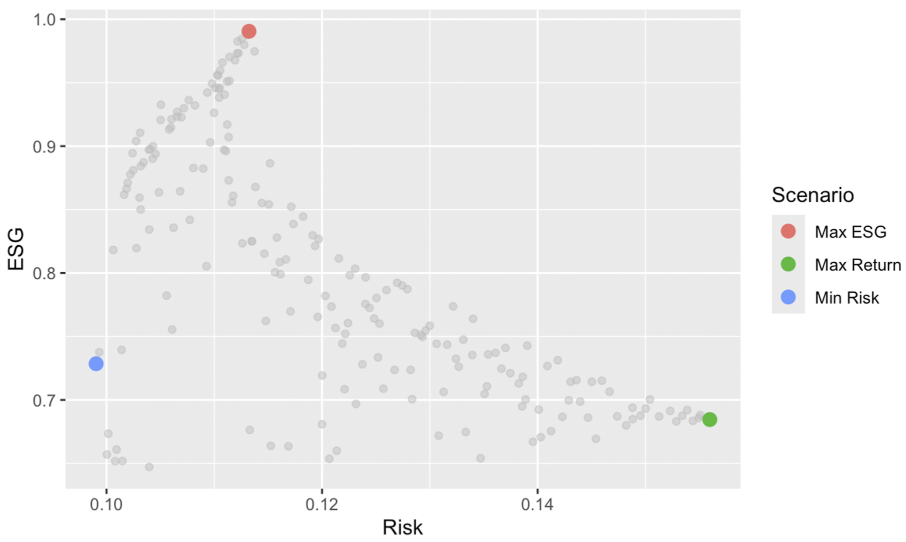

Figure 5. Risk vs ESG projection

reduced exposure of high-ESG firms to extreme downside events and enhanced stability through responsible corporate practices, which effectively lower portfolio variance without compromising expected returns.

The Return–ESG projection (Figure 4) shows that portfolios achieving high ESG scores can still deliver competitive returns. The modest reduction in expected return for ESG-prioritized portfolios aligns with the risk–return trade-off framework, indicating that incorporating ESG does not necessarily imply a severe financial penalty. This outcome can be explained by the tendency of high-ESG firms to exhibit stable cash flows, lower idiosyncratic risk and prudent management practices, which support portfolio returns while enhancing sustainability objectives.

Finally, the Risk–ESG projection (Figure 5) reveals that portfolios with higher ESG scores tend to cluster in regions of controlled volatility. This empirical pattern is consistent with financial theory suggesting that firms with strong ESG practices often exhibit lower idiosyncratic and systemic risk due to better governance, transparent reporting, and prudent operational management. As a result, ESG integration can act as a stabilizing factor, reducing downside risk without compromising returns.

Overall, these visual and analytical results move beyond a purely descriptive interpretation of efficient portfolios. They demonstrate that multi-objective optimization provides actionable insights for investors by explicitly quantifying the financial implications of sustainability preferences and highlighting feasible portfolio configurations that reconcile return maximization, risk control, and ESG performance. This theoretical and empirical linkage strengthens the practical relevance of the proposed framework for informed, responsible, and risk-conscious investment decision-making.

5.4 Distribution of portfolio metrics

Figure 6 presents the distribution of the simulated portfolio metrics (Return, Risk, and ESG scores) across the entire set of generated portfolios. This visualization highlights the range, central tendencies and variability of each criterion, providing insights into the diversity and feasibility of efficient portfolios within the multi-criteria optimization framework.

The histograms of Return, Risk and ESG scores provide an overview of the heterogeneity and range of the optimal portfolios. Most portfolios exhibit returns between 5% and 15%,

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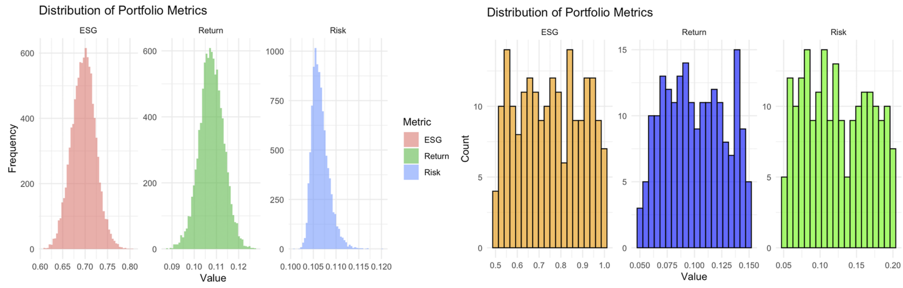

Figure 6. Distribution of simulated portfolio metrics (Return, Risk, ESG)

indicating a concentration of moderate investments. Volatility spans approximately 5%–20%, reflecting the diversity of risk exposures available for portfolio construction. ESG scores range from 0.5 to 1, highlighting substantial variation in sustainability performance among efficient portfolios. This figure complements the compromised solutions visualizations by illustrating the distributional characteristics of each criterion, offering investors and policymakers a comprehensive perspective on the feasibility and diversity of sustainable investment options.

The distributions indicate significant heterogeneity among the simulated portfolios. Returns exhibit a right-skewed pattern, characterized by a limited number of high-return portfolios that are typically associated with higher volatility.

This asymmetry reflects the classic presence of high-reward but high-risk strategies, which may be attractive to return-seeking investors but unsuitable for risk-averse profiles. Risk displays an approximately normal distribution centered around moderate volatility, suggesting that most efficient portfolios operate within a balanced risk range rather than at extreme levels. This concentration around moderate risk levels indicates that multi-objective optimization naturally filters out excessively risky solutions while preserving diversification benefits.

ESG scores follow a bimodal distribution, reflecting the coexistence of portfolios with either strong or relatively weak sustainability profiles. This pattern is economically meaningful, as it suggests that ESG integration is not incremental but rather reflects distinct strategic choices by investors, either explicitly prioritizing sustainability or focusing primarily on financial objectives. Such bimodality confirms that ESG acts as an active decision dimension rather than a passive by-product of financial optimization. Importantly, the presence of high-ESG portfolios within the optimal set demonstrates that sustainability-oriented strategies can remain competitive and efficient from a financial standpoint.

Figure 7 presents the relationship among portfolio Return, Risk, and ESG Performance, showing the distribution of portfolios as points and the underlying trends. The joint visualization highlights the interaction between financial performance and sustainability, revealing that higher ESG exposure is generally associated with controlled volatility and moderate returns. This reinforces the idea that ESG integration may contribute to portfolio stability rather than merely acting as a return constraint.

These distributional patterns are consistent with the findings of Benedetti *et al*. (2021) and Renneboog *et al*. (2008), who similarly show that ESG-integrated portfolios tend to exclude extreme high-risk configurations while preserving substantial heterogeneity in sustainability performance. This convergence reinforces the interpretation that ESG integration reshapes the feasible investment space by improving portfolio stability without eliminating opportunities for competitive financial returns.

5.5 Overall insights

Overall, the 3D and 2D Pareto analyses, combined with the distributional evidence, reveal a nuanced and economically meaningful relationship between financial and sustainability

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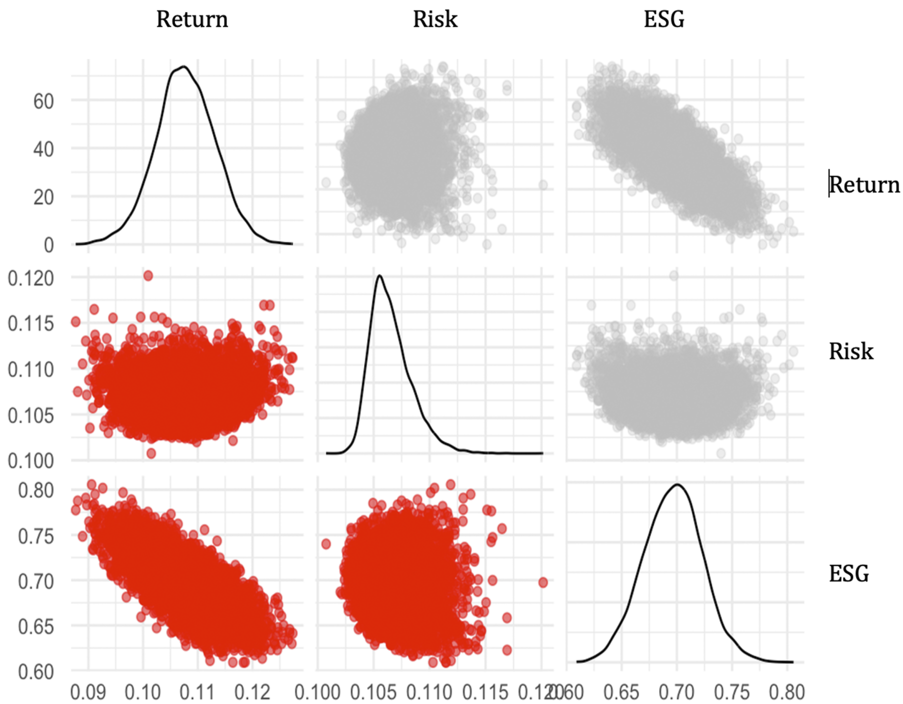

Figure 7. Relationship return, risk and ESG

objectives. Rather than indicating a strict trade-off, the results suggest that ESG integration reshapes the risk–return profile of portfolios by favoring stability and resilience over extreme performance outcomes. Sustainable portfolios do not systematically underperform; instead, they tend to occupy regions of moderate returns and lower volatility, which are particularly relevant for long-term and institutional investors.

These overall findings converge strongly with the broader ESG literature. For example, Friede *et al*. (2015) document that most empirical studies observe neutral or positive relationships between ESG and financial performance, which aligns with the competitive returns achieved by our ESG-prioritizing and balanced portfolios. The risk-mitigating effect of ESG identified in our analysis also reflects the conclusions of Khan *et al*. (2016) and Broadstock *et al*. (2021), who argue that firms with superior ESG practices exhibit more resilient and less volatile performance. At the same time, the modest return differences across portfolios mirror the mixed but generally neutral findings reported by Pedersen *et al*. (2021), confirming that ESG tends to enhance resilience rather than systematically increasing returns.

From an investment perspective, these findings imply that ESG should be viewed as a strategic portfolio characteristic rather than a constraint. The availability of a wide range of efficient solutions allows investors to explicitly align their portfolios with specific financial goals, risk tolerance and sustainability preferences. The evidence that meaningful improvements in ESG performance can be achieved with only marginal reductions in expected returns provides strong support for the economic viability of responsible investment strategies.

Finally, the results demonstrate the value of multi-objective optimization as a decision-support framework, as it exposes the full set of efficient compromise rather than imposing arbitrary weighting schemes. This approach enhances transparency, improves comparability across

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investment strategies and facilitates informed decision-making. By jointly considering return, risk and ESG performance, the framework offers a financially grounded and economically interpretable pathway for integrating sustainability into modern portfolio construction.

6. Conclusion

This study developes and empirically validated a tri-objective portfolio optimization framework that simultaneously integrates financial return, risk management and ESG performance within a unified decision model. The research is motivated by the growing necessity to align investment strategies with sustainability goals while maintaining competitive financial outcomes. By combining Pareto efficiency and weighted goal programming, the proposed model contributes to bridging the gap between classical quantitative finance and responsible investment practices, offering a rigorous methodological foundation for multi-criteria portfolio construction.

The empirical results, based on ESG data from Refinitiv Asset4 for 100 international firms observed over the 2018–2023 period, reveal several key insights. Analysis of the Pareto front confirms the presence of significant interactions between profitability, volatility and sustainability objectives. Portfolios with higher ESG performance tend to show slightly lower returns but substantially reduced risk exposure, indicating that sustainability can enhance portfolio stability without severely compromising profitability.

From a financial standpoint, this indicates that investors can achieve a more favorable risk-return profile by integrating ESG criteria, as sustainability can act as a stabilizing factor in volatile markets. The trade-offs quantified in this study provide actionable guidance for portfolio construction, enabling investors to select allocations aligned with their risk tolerance, return expectations and sustainability objectives.

These findings carry immediate practical implications. Investors and portfolio managers can apply the model to construct portfolios that simultaneously meet financial objectives and sustainability targets, optimizing risk-adjusted returns while enhancing ESG performance. Regulators and policymakers can also draw on these insights to promote responsible investment practices, shape disclosure requirements and support market mechanisms that embed ESG considerations into mainstream financial decision-making.

In addition, the model provides practitioners with a structured decision-support tool that quantifies the trade-offs among return, risk, and ESG performance, enabling more transparent communication with stakeholders. The ability to identify a “balanced zone” of portfolios also offers asset managers a practical benchmark for aligning investment mandates with regulatory ESG requirements and long-term sustainability objectives.

Furthermore, the results highlight the existence of a balanced portfolio zone where investors can achieve an optimal compromise between financial and societal objectives, making the model highly relevant for practitioners aiming to integrate ESG factors into modern portfolio theory.

From a theoretical perspective, this research advances sustainable finance by operationalizing multi-criteria optimization techniques in portfolio selection. It extends the traditional mean–variance frameworks by incorporating ESG as a strategic dimension of performance evaluation, emphasizing that ESG integration is not merely an ethical constraint but also a factor enhancing long-term portfolio resilience. Practically, the model offers a valuable analytical tool for stakeholders, enabling visualization of the interactions among competing objectives and supporting evidence-based decision-making in responsible investment management.

Moreover, by empirically demonstrating the interaction structure between financial and sustainability objectives, the study offers theoretical support for the view that ESG constitutes an endogenous component of portfolio efficiency rather than an external constraint. This reinforces contemporary theoretical developments positioning sustainability as a determinant of long-term risk-adjusted performance.

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This applicability underscores that ESG factors should be treated as strategic levers capable of improving portfolio stability and fostering long-term value creation, reinforcing the financial rationale for sustainable investing.

Despite the robustness of the proposed framework, some aspects merit further investigation. The current analysis, based on historical data, captures static relationships between return, risk and ESG performance. These interactions are inherently dynamic and may evolve with market cycles, regulatory changes and shifting investor preferences.

From a research standpoint, several opportunities emerge to extend this work. Future studies could implement dynamic or stochastic multi-objective optimization frameworks, incorporate more granular ESG dimensions, or leverage machine learning techniques to improve predictive capabilities. Additionally, cross-country or sectoral analyses could shed light on how institutional and economic contexts shape the interplay between financial performance and sustainability outcomes.

Overall, the theoretical and practical implications derived from the findings highlight the relevance of integrating ESG factors within formal portfolio models and demonstrate how multi-objective optimization can enhance both the conceptual understanding and the operational implementation of sustainable investment strategies.

In conclusion, this study provides both theoretical and practical contributions to ESG portfolio optimization. It demonstrates that responsible investment can be achieved through rigorous analytical models that balancing return, risk and sustainability objectives. By quantifying these trade-offs and revealing the stabilizing role of ESG performance, the study contributes to the ongoing transformation of financial markets toward a more sustainable and resilient global investment paradigm.

Overall, the findings confirm that multi-objective optimization is a robust framework for translating sustainability ambitions into actionable investment strategies, effectively bridging the gap between theoretical finance models and practical responsible investment practices.

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