Exploring Distributive Justice In Many-Objective Optimization

A Comparative Analysis of A Priori and A Posteriori Approaches to Implementing Distributive Justice Principles

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by

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at the Delft University of Technology,

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Model and data files are available at
https://github.com/MeronZnabei/master-thesis-project

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Preface

I would like to express my gratitude to several individuals who played instrumental roles in the completion of this thesis.

Firstly, I extend my sincere thanks to Jazmin for sparking my interest in this thesis topic threw her enthusiasm and for providing a wealth of valuable references to transform this interest into the depth the research contains now. Her warm invitation to the research group, the Hippo Lab, not only facilitated discussions on shared factors across lab members and me but also ensured that the thesis period became a time for learning about a broader context than just the scope of this research. Neelke's motivation and encouragement were pivotal in giving me the courage to delve into the ethico-philosophical theories and questions behind my applications. Having discussions with Jan on my problem formulations and result visualizations greatly enhanced the clarity and effectiveness of my research. His probing questions encouraged me to critically assess my approach and defend it with conviction, fostering a sense of ownership over my work. This mentorship has been instrumental in shaping my identity as a researcher, imparting a sense of seriousness and autonomy that is particularly gratifying as I conclude my master's journey.

Special thanks to Tigist and Yannick, who consistently offered me a focused space, akin to a self-proclaimed thesis incubator, whenever I faced challenges or roadblocks. Their support played a crucial role in overcoming hurdles during the research process. I am deeply grateful to my mom for her unwavering support throughout my study. Her active involvement made the journey feel like a shared goal, and this report is dedicated to her. Lastly, I would like to express my appreciation to my friend Alix, who graduated earlier and, during her thesis period, advocated for the often-overlooked thesis objective and her theory of '10 for well-being'. Alix's example demonstrated that achieving a balance can indeed be a legitimate thesis objective, proving that there doesn't have to be a trade-off between academic excellence and personal well-being.

In conclusion, thank you for taking the time to read my work, acknowledging the effort I've put into it.

Executive Summary

Water scarcity, a pressing global concern impacting both the environment and human well-being, underscores the importance of effective water resource management. The United Nations' Sustainable Development Goal 6 emphasizes the need to ensure water availability and sustainable management. Central to the water-management is the control of dams in river basins, posing complex decision-making challenges, often considered wicked problems. Many-Objective Optimization, applied in modeling water systems, addresses conflicting objectives but becomes more intricate when considering Distributive Justice principles. Distributive Justice aims to equitably distribute resources among society members, crucial in water distribution for reservoir management. While currently Distributive Justice in modeling is mostly applied A Posteriori, this study focuses on incorporating these principles of Distributive Justice A Priori and assessing their impacts on trade-offs and decision-making processes within Many-Objective Optimization. The research seeks to answer the fundamental question:

"How to incorporate Distributive Justice Principles within Many-Objective Optimization Modeling?"

Sub-questions delve into diverse perspectives on Distributive Justice principles, their translation into mathematical models, observed trade-offs, and a comparison of A Priori and A Posteriori integration.

Diverse perspectives within Distributive Justice exist and are explored in this study, introducing key ethical frameworks—Utilitarianism, Egalitarianism, and Prioritarianism. Utilitarianism prioritizes maximizing overall happiness or well-being but faces critiques for potential injustices in distribution and challenges in defining the currency for justice. Egalitarianism advocates for equal distribution of goods, yet debates persist on defining the baseline for equality, and the leveling down principle questions its impact on societal well-being. Prioritarianism emphasizes the needs of the least advantaged, utilizing a transformation function, with critiques centering on neglecting other justice aspects and challenges in parameter choices. Each framework offers a distinct lens on just distribution, catering to varied societal values, and understanding their implications is vital for informed policy optimization decisions. This study adopts a consequentialist approach to translate these Distributive Justice theories into rankings of consequences. The Social Welfare Framework is introduced as a tool for policy assessment. emphasizing the importance of understanding these ethical principles for policymakers.

The ethical frameworks set the stage for empirical application. The methodology employed in this study centers around the Evolutionary Multi-Objective Direct Policy Search framework, specifically focusing on reservoir management optimization within the Eastern Nile River Basin. EMODPS integrates a non-linear approximating network as a policy function into a simulation model, refining parameters through Multi-Objective Evolutionary Algorithm runs. The Epsilon Non-dominated Sorting Genetic Algorithm-II is chosen as the MOEA due to its effectiveness in handling many-objective optimization problems. The study aims to compare A Priori with A Posteriori results, assessing the impact of incorporating distributive justice principles in optimization outcomes. The experimental setup to achieve this involves running optimizations for a reference problem formulation and three distributive justice principle formulations based on the previous mentioned Utilitarian, Egalitarian, Prioritarian frameworks. The reference problem formulation consists of the following six deficit objectives that ought to be minimzed with their respectitive objective function *1) Egypt Average Yearly Irrigation Demand Deficit*, *2) Egypt 90th Percentile Worst Demand Deficit*, *3) Egypt HAD Level Deficit*, *4) Sudan Average Yearly Irrigation Demand Deficit*, *5) Sudan 90th Percentile Worst Demand Deficit*, and *6) Egypt Hydropower Demand Deficit*. Distributive Justice is evaluated using added problem formulations of which the direction of preference is maximization for the first two and minimization for the final of the following objectives *7) Utilitarian*, *8) Prioritarian*, and *9) Egalitarian*.

The Reference Experiment reveals trade-off patterns among original objectives, showcasing the complexities in balancing conflicting interests. A Posteriori evaluation using the Distributive Justice Principles identifies nuanced optimal policies. A Priori integration of these fairness formulations results in distinctive Pareto approximate sets, influencing the trade-offs observed. Utilitarian integration marginally increases overall system performance, while Egalitarian integration expands the solution space, demonstrating potential for compromise solutions. Prioritarian integration prompts trade-offs, indicating challenges in reconciling distributive justice principles. An A Posteriori Prioritarian evaluation shows clearly which solutions that seem favorable in the reference setting, are highly unfavorable from a Prioritarian point of view. Integrating the principle A Priori did show unexpected behavior of the solutions scoring lower on average for the Prioritarian objective when optimized using that same Prioritarian problem formulation. A comprehensive exploration of the 10^{th} percentile solutions highlights divergent preferences.

The study is aware of limitations affecting the robustness of its findings. The incommensurability of objectives in the simulation model, like Egypt's irrigation deficit and Ethiopia's hydropower deficit, challenges the justification of prioritization due to the lack of a common scale for comparison. Sensitivity issues arise with Atkinson social welfare functions, especially for Prioritarianism, as they require non-negative well-being values and exhibit anomalies near zero thresholds. Aggregating welfare within a single group may exclude disadvantaged subgroups in the Social Welfare Framework. The simulation model lacks considerations for flooding and oversimplifies irrigation districts in Sudan. Additionally, the study does not integrate the Equality of Opportunity Theory. Addressing these limitations is crucial for a more comprehensive understanding of water resource management decision-making. Nevertheless, the incorporation of Distributive Justice principles, both A Priori and A Posteriori, showcases its distinct potential to positively influence the relevance and depth of results in Many-objective Optimization studies.

Showcasing this significantly contributes to the field of Many-objective Optimization, thereby expanding the conventional Many-objective Optimization framework. The exploration of ethical views within Many-Objective Optimization sheds light on how and when incorporating different principles influence the Pareto approximate set and trade-off landscapes, contributing to the broader discourse on ethical considerations in optimization. The societal relevance is emphasized through the study's focus on the Eastern Nile River Basin, where trade-offs and conflicts between Distributive Justice principles and original objectives carry implications for marginalized communities. Future directions could involve exploring other principles of distributive justice, considering covariance for result interpretation, and developing a framework for the effective use and communication of the additional information obtained through the incorporation of distributive justice principles A Priori in decision-making processes.

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Acronyms

EA Evolutionary Algorithm. 29

EMODPS Evolutionary Multi-Objective Direct Policy Search. 19, 20, 27

ENRB Eastern Nile River Basin. 6, 21, 22, 24, 32, 33, 46, 48

GERD Grand Ethiopian Renaissance Dam. 21, 30, 54

MOEA Multi-Objective Evolutionary Algorithm. 19, 20

MOO Multi-Objective Optimization. 11, 14, 32, 46

NSGAII Non-dominated Sorting Genetic Algorithm II. 20

RBF Radial Basis Function. 28

SDG Sustainable Development Goal. 10

SWF Social Welfare Function. 15, 16, 18, 44

ε-NSGAII Epsilon Non-dominated Sorting Genetic Algorithm II. 20, 27, 55

1

Introduction

Water scarcity is a critical global issue with significant impacts on the environment and human well-being. The United Nations, Department of Economic and Social Affairs - Sustainable Development (2022) highlights this in Sustainable Development Goal (SDG) number six, which calls to ”Ensure availability and sustainable management of water and sanitation for all.”. Managing water resources in river basins is essential, and dam construction is a common method for controlling water availability in these areas (Zarfl et al., 2015). However, building a new dam necessitates balancing the interests and needs of various stakeholders, including multiple countries, resulting in decision-making challenges (Swain, 2011). Such a complex decision-making scenario is deemed a wicked problem (Ackoff, 1978) due to its complex and interrelated challenges (Rittel and Webber, 1973). Many-Objective Optimization can be employed to model water systems and their conflicting objectives (Sari, 2022). Many-Objective Optimization is a specific type of multi-objective optimization where there are more than three or four objectives that need to be optimized, making it a more complex problem to solve (Chand and Wagner, 2015). This complexity is further compounded when considering the principles of Distributive Justice, which are crucial for ensuring equitable allocation of water resources among various stakeholders (Doorn, 2013).

Distributive Justice refers to the idea of fairly distributing resources, benefits, and burdens among members of a society (Lamont, 2017). In the context of water distribution in reservoir management, Distributive Justice considers how to allocate the limited water resources in a fair and equitable manner among different stakeholders, such as households, agriculture, and industry (Giuliani et al., 2021). Several principles of Distributive Justice exist, including Utilitarianism, Prioritarianism, and Egalitarianism (Freeman, 2018). Most water-system modeling employs a Utilitarian principle for optimization (Groenfeldt and Schmidt, 2013), which aims to maximize happiness or well-being for the most significant number of people (Sen, 1979). However, it is debatable whether SDG6 concerning water aligns with a Utilitarian perspective, as Utilitarianism accepts inequality if it results in greater group utility. Conversely, Prioritarianism contends that resources should be allocated to benefit the least advantaged members (Adler and Norheim, 2022). In the context of water distribution, this could mean allocating water to meet the basic needs of marginalized communities before fulfilling the demands of more affluent groups. Egalitarianism, meanwhile, holds that natural resources, benefits, and burdens should be distributed equally among members of a society (Kolm, 1977). This means ensuring that everyone has access to an equal amount of water, regardless of their wealth, status, or location (Jeffrey, 2018). Besides these three, there are many other principles upon which natural resources can be distributed.

Current research in the fields of water management and Many-Objective Optimization promotes the incorporation of inter-country Distributive Justice in modeling (Yalew et al., 2021). However, the existing approach predominantly involves A Posteriori evaluation of the optimization policy results against distributive fairness (Tian et al., 2019; Sarva, 2021), rather than directly incorporating the ethical values of a chosen principle A Priori in the optimization. While few studies, such as the work by Ciullo et al. (2020), do exist that A Priori incorporate and compare the effects of different Distributive Justice principles, these applications tend to be case-specific, containing commensurable outcomes and partly relying on case-specific constraints, which limit their generality. Additionally, existing research lacks a comprehensive comparison between A Priori and A Posteriori approaches applied to the same case.

> ***A Priori*** — A Priori refers to the incorporation of a problem formulation at the optimization stage of the modeling process in order to evaluate in-processing.
>
> ***A Posteriori*** — A Posteriori involves the evaluation of the optimization results against a problem formulation as a post-processing filter, after the optimization has been performed.

This research seeks to contribute to the field in three key aspects. It aims to establish and apply clear terminology distinguishing A Priori and A Posteriori evaluation of Distributive Justice principles. Furthermore, it endeavors to develop a general framework for the A Priori application of Distributive Justice principles in Many-Objective Optimization. Finally, it addresses the gap by providing a comparative analysis of A Priori versus A Posteriori approaches. Importantly, this research takes an agnostic stance on whether one approach should be favored over the other, focusing instead on studying pathways for implementing this normative choice.

This thesis is designed to answer the following research question:

How to incorporate Distributive Justice Principles within Many-Objective Optimization Modeling?

1.1. Research Questions

For answering the main research question, the following sub-questions are addressed:

1. *What are different perspectives on commonly used Principles of Distributive Justice?*
   In the realm of philosophy, there are numerous approaches to distributive justice, each accompanied by varying perspectives. Understanding these approaches, and how their principles can be quantified through the social welfare framework, is crucial. This knowledge provides a basis for decision making regarding using these principles in MOO.

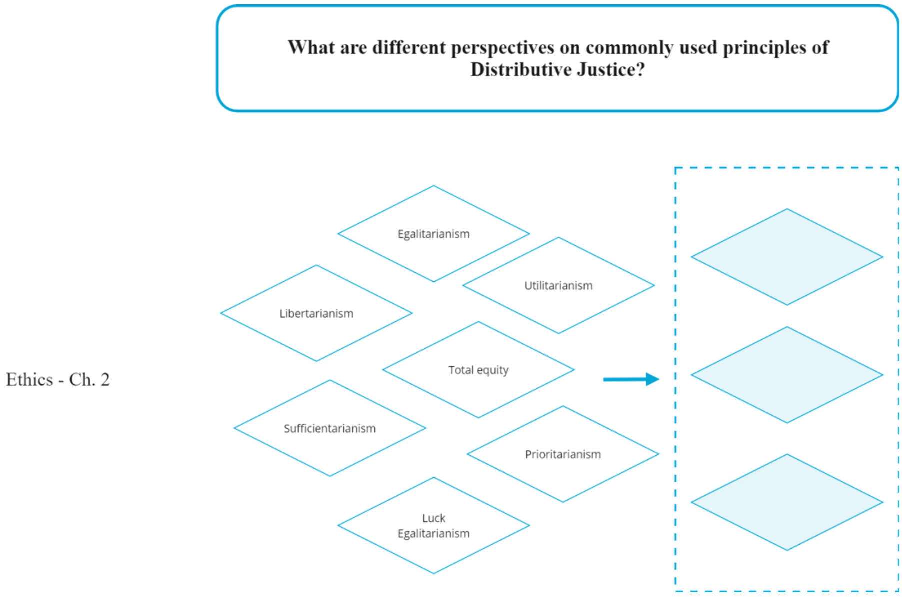
2. *How and at which step of the modeling process can Distributive Justice principles be embedded into a Many-Objective Optimization model?*
   The different principles and their philosophical views need to be translated towards a mathematical formulation to be able to include them in modeling. This ensures that the incorporation of distributive justice is not only theoretical but also operational, offering a tangible framework for ethical considerations in complex optimization scenarios.

3. *What trade-offs are observed when evaluating the Many-Objective Optimization model using different Distributive Justice principles A Posteriori?*
   Incorporating ethics in decision-making can be done both A Priori and A Posteriori. The latter being the common practice. A baseline model is evaluated against each Distributive Justice principle A Posteriori. This will show the new trade-offs that would have been found with the traditional method of evaluating Distributive Justice.

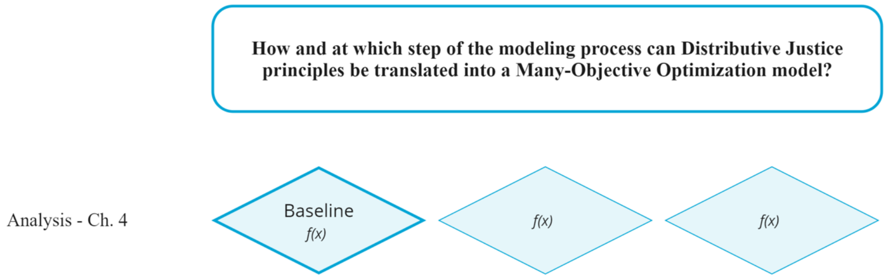
4. *How does A Priori integration of Distributive Justice principles in a Many-Objective Optimization model compare to evaluating them A Posteriori?*
   It is expected that models based on different Distributive Justice principles (A Priori) will yield significantly different results for the trade-offs. The models that have included the Distributive Justice principles A Priori will be compared to the baseline model. This analysis, with results from previous sub-questions, will inform a new methodology for including Distributive Justice principles in many-objective optimization for answering the main research questions.

1.2. Research Approach

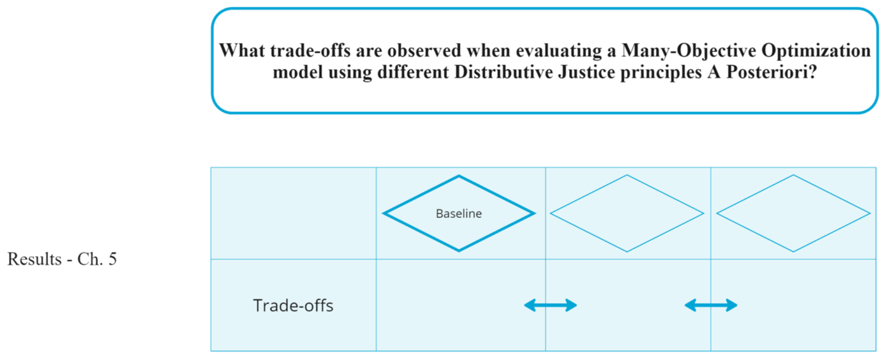
The research encompasses distinct chapters, each addressing specific facets of integrating Distributive Justice principles into Many-Objective Optimization. A holistic overview of these chapters and how they link to each research question provided in the previous section is provided in figure 1.1. Chapter 2 will explore key ethical concepts and address the crucial question of which specific Distributive Justice principles are most pertinent for integration within the scope of this research. Subsequently, Chapter 3 meticulously delineates the methodological strategies employed to translate these theoretical principles into precise mathematical formulations, thereby providing a systematic response to the second research query. Chapter 4, the Analysis chapter, is dedicated to the meticulous evaluation of the Many-Objective Optimization model under diverse Distributive Justice principles, thereby addressing the third research question. Chapter 5 explores the results from the A Priori integration of these principles into the model and compare these outcomes with the conventional A Posteriori evaluation. These chapters specifically respond to the fourth and fifth research questions. Finally, the Discussion, chapter 6 and Conclusion, chapter 7, synthesize and reflect on the findings in order to address the overarching research question, thereby contributing to the scholarly discourse in the field.



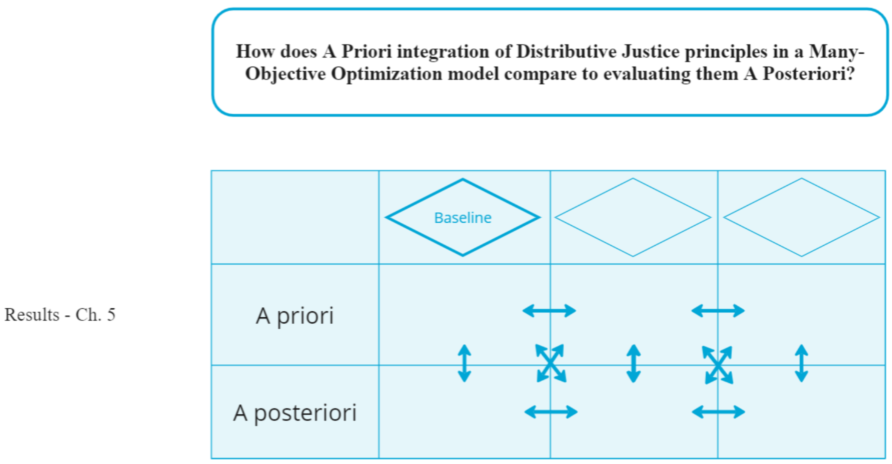
(a) Highlighting the perspectives on a subset of Distributive Justice principles that are integrated within this study.



(b) Deciding on the mathematical formulation of the three chosen Distributive Justice principles, of which one forms the Baseline.



(c) A Posteriori evaluation, comparing the trade-offs between the different problem formulations.



(d) Introducing an additional A Priori evaluation layer to facilitate a comparison between the trade-offs at different processing steps of the evaluation, creating a cross-comparison.

Figure 1.1: Schematic illustration of the research approach for each research step, showcasing the associated research question and the respective chapter where the content is detailed.

2
Ethical Frameworks

The introduction emphasized the need for incorporating Distributive Justice into policy optimization. To technically integrate Distributive Justice into MOO, a foundational understanding of the philosophical question surrounding what constitutes a just distribution is essential. This chapter aims to unravel this question by initially explaining the overarching concept of Distributive Justice. Subsequently, it delves into an in-depth exploration of various ethical frameworks within Distributive Justice.

2.1. Distributive Justice

Distributive Justice is a concept that originates from the normative ethical principle of justice, collectively shaped by philosophers like Rawls (1971), Nozick (1974), Sen (1999), among others. It is one of the four cardinal virtues in classical moral philosophy, alongside wisdom, courage, and temperance. Justice is the principle of fairness and moral rightness, ensuring equitable treatment, protection of rights, and the ethical distribution of resources and opportunities in society. Distributive Justice, specifically, is a subset of justice that deals with the distribution of goods, benefits, and burdens among the members of a society. It is concerned with answering the question of who gets what, and why.

Theories of Distributive Justice can be examined based on their approach to three critical issues: scope, shape, and currency (Page, 2007). The scope of justice pertains to identifying the legitimate recipients of benefits and burdens in society. This raises questions about which entities hold value and claims against others. Within this framework, there are various positions, such as focusing on humans alone, including non-human animals, extending to all living creatures, or even encompassing certain physical structures or processes. Even within a human-centric paradigm, there are further considerations, including spatial and temporal limits of justice, determining whether only contemporaneous compatriots, people from all countries in the same era, or all individuals throughout history have distributive claims. Additionally, there is the issue of identifying responsible entities or institutions for providing benefits outlined by any distribution theory. The shape of justice concerns the pattern of benefits recommended by a distribution theory, determining how much advantage individuals should receive. Common responses to this question include efficiency, equality, priority, and sufficiency. These theories advocate for maximizing human (or animal) well-being, ensuring equality, improving the welfare of the worst-off groups, or guaranteeing that as many people as possible have sufficient resources for a good life. The currency of justice refers to the aspect of well-being, or the unit of benefit or advantage, upon which distributive concerns should focus. It implies that a comprehensive account of entities deserving justice must be linked to a clear understanding of what is shared among these entities. Suggestions for the focus of distribution across society include welfare, opportunities for welfare, basic capabilities to function, and access to advantage.

Even-though Distributive Justice theories differ in these three units; scope, shape and currency, they adopt a consequentialist approach in measuring what is just. In contrast with other views on justice such as a deontological view, Consequentialism weighs the moral quality of an action solely by looking at the action's consequences, relative to the consequences of alternative actions open to the decision-maker (Driver, 2011). The following chapters will focus on translating Distributive Justice theories in rankings of consequences. The main focus of this study is to identify the effect of different shapes of distribution on the justification of ranking actions. This leads to the first main assumption of this study, *1)* there is consensus on the scope, the recipients that benefit from the actions. Furthermore, *2)* a welfarist approach is assumed to be fitting for the currency of these benefits. The benefits of a welfarist approach to measuring well-being have been argued by Adler and Norheim (2022). Welfare refers to the total well-being or utility of all individuals in a society. Social Welfare Economics is the comparative assessment of alternative "outcomes", "allocations" or "states of the world" on the basis on explicit normative social desiderata (Adler and Norheim, 2022). While Distributive Justice provides the philosophical foundations discussing what is "fair" or "just", Social Welfare Economics offers tools and frameworks to operationalize these concepts. The following section formulates how social welfare can be applied to different shapes of distribution.

2.2. The Social Welfare Framework

Literature on theoretical Welfare Economics nicely uses axioms to specify different Social Welfare Functions. A Social Welfare Function (SWF) is a mathematical representation used in welfare economics for policy assessment. A SWF consists of three components: (1) A measure of well-being $W(\cdot)$ that converts policy-choice outcomes x into well-being vectors $W_1(x), ..., W_N(x))$. (2) A rule for ranking these vectors, tailored according to the ethical view. (3) A component to assess uncertainties, by ranking policies as probable distributions over well-being vectors. Every plausible SWF satisfies two basic axioms: the Strong Pareto, and Anonymity (Adler and Norheim, 2022). The Strong Pareto axiom stems from Pareto Optimality theory by Pareto (1906), which represents a state of allocation of resources where it is impossible to make any individual better off without making someone else worse off. An example for a Strong Pareto ranking would be $(3,4,10,13) > (3,4,10,12)$. Anonymity shows the ethical indifference to whom the benefit is passed , exampled by $(7,12,4,60) \sim (12,60,4,7)$.

As mentioned in section 2.1, several principles can affect the shape of what is seen as a just distribution. Social Welfare Function (SWF) methodology is used to formalize the principles as a specific family of SWFs. Some of the most well-known and widely discussed principles of Distributive Justice are Utilitarianism, Prioritarianism, and egalitarianism. Their axioms, SWFs and exposed critiques by scholars are discussed next.

2.2.1. Utilitarianism

The Utilitarian principle holds that goods and benefits should be distributed so as to maximize overall happiness or well-being. It is originally invoked by Bentham (1789) and his principle of the greatest happiness for the greatest number.This concept has been further explored in welfare economics theories, such as the more recent works by Adler (2019); Sen (2018), resulting in the formulation of the following Utilitarian SWF:

$$S^{Utilitarian} = \sum_{l=1}^{N} w_l(x) \tag{2.1}$$

The Utilitarian SWF calculates overall social welfare ($S^{Utilitarian}$) as the sum of individual well-being ($w_l(x)$) for each person (l) in the population (N). Mill (1863) significantly popularized utilitarian ethics through his nuanced elaborations and defenses, greatly influencing the philosophical understanding and broader acceptance of it as the default theory for welfare analysis. However, utilitarianism has been criticized by different scholars for potentially justifying the sacrifice of the well-being of a minority for the greater good of the majority. There are two main critiques on the principle. The first critique has been early-on stated by economists, such ass Bergson (1938); Samuelson (1947); Atkinson (1970).

Critique 1: The currency for justice should be opportunities (choice sets), not final welfare. As a consequence different kinds of inequality matter differently, depending on the role of personal responsibility. The Equality of Opportunity Theory discussed by Dworkin (1981); Arneson (1989); Roemer (1985) elaborates on this. It focuses on both the Principle of Compensation, which holds that differences in "circumstances" beyond the control of the individuals warrant compensation, as they generate unfair inequalities in well-being, and the Principle of Reward, which claims that "efforts" should be rewarded and the resulting inequalities in well-being should be preserved. While it is important to highlight this critique, it is not tackled within this study.

Critique 2: This second critique focuses on the aggregation rule used for the Utilitarian SWF, which is a simple summation of well-being. This leads to possible inequality in the distribution of well-being. Philosophers like Sen (1980) have long emphasized this issue. Within this critique lies a normative belief that people with a lower well-being level deserve priority in the design of public policy.

This belief created support for families of SWFs that satisfy the Pigou-Dalton axiom. The Pigou-Dalton axiom is a concept in welfare economics that deals with the redistribution of resources or wealth within a society (Adler, 2019). According to this principle, a transfer of resources from a individual at a higher well-being level to a lower one will increase overall social welfare, making the distribution of wealth more equal. An example ranking is $(3, 6, 8, 12) > (3, 4, 10, 12)$. In contrast with Utilitarianism, the following two principles Egalitarianism and Prioritarianism both satisfy Pigou-Dalton.

2.2.2. Egalitarianism

This principle holds that goods and benefits should be distributed equally among all members of a society, which is a principle of equality. In welfare economics, scholars such as Kolm (1977) have explored egalitarian perspectives, leading to the development of different social welfare functions inline with the following:

$$S^{Egalitarian} = \sum_{l=1}^{N} \left(w_l(x) - \lambda \times \left| w_l(x) - \mu \right| \right) \tag{2.2}$$

This formula represents an egalitarian SWF ($S^{Egalitarian}$) that calculates social welfare by considering the absolute differences between individual well-being ($w_l(x)$ and the mean (μ) weighted by a parameter (λ). Formula 2.3 is the Gini Index (Gini), an inequality metric that measures overall income or well-being disparity in a population by summing the absolute differences between all possible pairs of individuals (w_i) and (w_j) and normalizing the result (Gini, 1921). Despite being an inequality measure, the Gini Index is chosen as a social welfare function because it captures the distributional aspect of well-being, providing insights into overall societal inequality. The first formula is less used due to challenges in defining a clear baseline for equality, while the Gini Index offers a comprehensive quantitative measure of inequality that can be applied to social welfare analysis.

$$\text{Gini Index} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |w_i - w_j|}{2n^2 \bar{w}} \tag{2.3}$$

Egalitarianism, however, faces its own set of critiques, of which the first main critique is, Critique 1: Defining the baseline for equality is one of the aspects with little consensus. The Equality of Opportunity Theory, also discussed as a critique of Utilitarianism argues that compensating for differences in circumstances beyond individuals' control is crucial to rectifying unfair inequalities. Simultaneously, rewarding efforts and preserving resulting well-being disparities add layers of complexity to the egalitarian approach. This is also a critique not dealt with within this study.

Critique 2: Another criticism is the leveling down principle introduced and argued by (Parfit, 1995). This critique challenges egalitarianism by highlighting the possibility that pursuing greater equality might result in an overall decrease in societal well-being. The leveling-down principle emphasizes the need for egalitarian approaches that not only address inequalities but also ensure that the overall welfare of society is not compromised in the pursuit of equality.

This critique has given rise to a division within the realm of egalitarianism, distinguishing between pure telic egalitarians and pluralist telic egalitarians. Pure telic egalitarians concentrate on achieving intrinsic equality, prioritizing equal distribution regardless of other considerations. Conversely, pluralist telic egalitarians advocate for the integration of additional principles into the pursuit of equality, recognizing the importance of factors such as overall societal well-being (Lippert-Rasmussen, 2018).

This discourse in Egalitarianism has led to the further exploration of theories that seek a delicate balance between equality and the broader welfare of society. Furthermore, it has sparked interest in principles that not only adhere to the Pigou-Dalton principle but also align with the separability axiom, marking a departure from an exclusive focus on the intrinsic value of equality. The separability axiom in welfare economics posits that individuals' preferences or well-being comparisons concerning specific attributes should remain consistent even with the introduction of irrelevant factors (Moulin, 1985). Consequently, the ranking of options based on relevant attributes should remain unchanged, irrespective of the presence or absence of irrelevant factors. In essence, this principle ensures that individuals' preferences remain stable across different scenarios. Mathematically, this can be expressed as $(7, 100, 100, 7) \succcurlyeq (4, 100, 100, 12)$ if and only if $(7, 7, 7, 7) \succcurlyeq (4, 7, 7, 12)$

2.2.3. Prioritarianism

This principle holds that goods and benefits should be distributed so as to benefit those who are worst off or least advantaged (Parfit, 1995). It is similar to Egalitarianism but gives priority to the needs of the least advantaged. The reason for this can be explained by comparing well-being numbers in the concave transformation function, in figure 2.1.

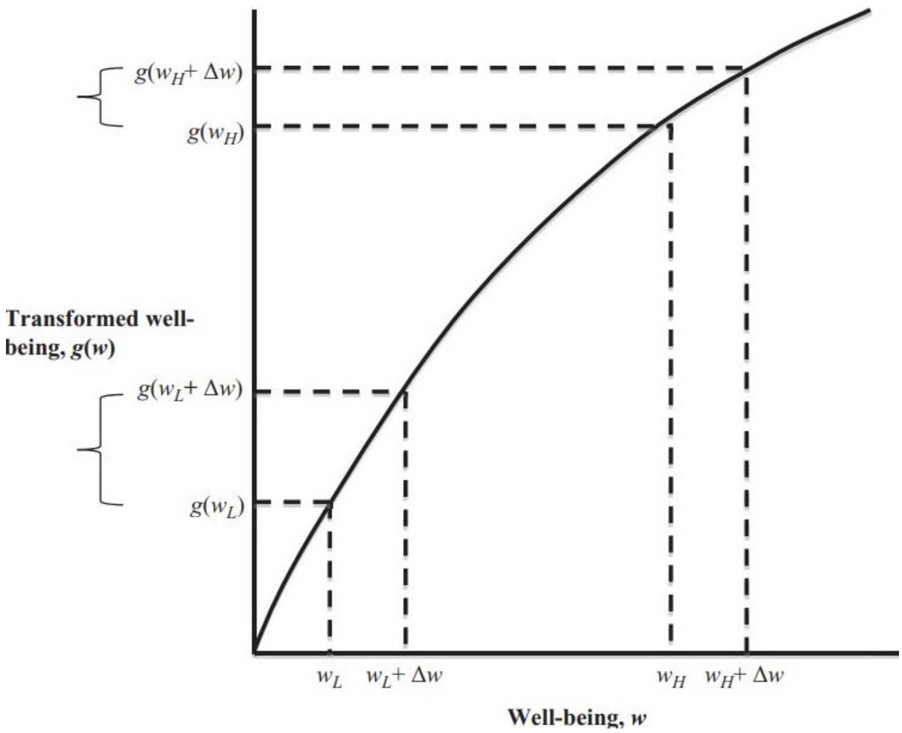


Figure 2.1: Comparing the effect of an equal well-being increment, Δw, on the transformed well-being value, $g(w)$, for a lower well-being value, W_L, and a higher well-being value, W_H, by displaying the concave transformation function, from Adler and Norheim (2022).

The function takes the form of a concave transformation because it assigns diminishing marginal weight to increases in well-being for individuals as their well-being improves. Specifically, it gives greater weight to improvements in well-being for individuals with lower initial well-being levels. This can be seen in figure 2.1. Consider two individuals, one worse-off with a well-being level W_L and another better-off with a well-being level W_H, where $W_L < W_H$. The figure shows the effect of two distinct policies: first, adding a given amount of well-being, Δw, to the worse-off person, and second, adding the same amount, Δw, to the better-off person. Due to the strictly increasing nature of $g(\cdot)$, both changes result in an increase in the Prioritarian score. However, owing to the strict concavity of $g(\cdot)$, the first change yields a more substantial increase in the Prioritarian score compared to the second. This concavity reflects the Prioritarian idea that prioritizing the well-being of the least well-off is more valuable than similar improvements for those who are already well-off.

In the context of many-objective optimization, this transformation is often applied to individual well-being values before aggregating them into a social welfare function. The transformed values are then used to assess the overall welfare of a society, considering both the well-being levels and the priority given to the worse-off. This implies a Prioritarian SWF ($S^{Prioritarian}$) of the following form, in which welfare (w_l) is transformed by transformation function g that is positive ($g'(w) > 0$), and strictly concave ($g''(w)$):

$$S^W = \sum_{l=1}^{N} g(w_l) \quad \text{where} \quad g'(w) > 0 \quad \text{and} \quad g''(w) < 0 \tag{2.4}$$

Atkinson SWFs follow this Prioritarian form. It is also the most discussed form due to the elaborate description by Atkinson (1970). In the current study the following transformation function is applied to form such a Atkinson Prioritarian SWF:

$$S^{Prioritarian} = \begin{cases} \frac{(w_l(x)-w_{zero})^{(1-\gamma)}}{1-\gamma}, & \text{if } \gamma \neq 1 \\ ln(w_l(x) - w_{zero}), & if \gamma = 1 \end{cases} \tag{2.5}$$

This transformation is done using a parameter γ , which determines the degree of priority we give to those who are worse off in society. A larger value of γ means that we're placing more emphasis on improving the welfare of those who are less fortunate. If we refer back to figure 2.1, a larger value of γ means a flatter, more concave, curve. There's a special case when $\gamma = 1$. In this situation, the transformation function becomes the logarithm of the individual's well-being.

A justification for adopting the specified form of a Prioritarian SWF lies in its classification as a Profile-independent SWF. A ”profile-independent” SWF maintains a consistent structure or shape of the SWF regardless of the specific metric employed for measuring well-being (Adler and Norheim, 2022). This implies that irrespective of whether well-being is assessed in terms of financial resources, health outcomes, or other dimensions, the same governing rule or SWF is applied for comparing and ranking different scenarios or policies. This approach aligns with the concept of ”welfare-consequentialism,” emphasizing the consideration of the distribution of well-being when comparing scenarios, regardless of the distinct factors (such as income, health, etc.) contributing to that distribution.

2.3. Conclusion

It becomes evident that there is no singular definitive answer to the question posed in the introduction of this chapter: 'What is a just distribution?' Instead, a multitude of ethical viewpoints are translated into principles guided by their respective axioms. Implementing such principles within policies yields varying effects based on the context, and different principles target different segments of a given society. The role of an analyst working with a Multi-Objective Optimization (MOO) model is not to make these value judgments, but rather to provide decision-makers with information about the ethical foundations underpinning various aggregation approaches, along with their corresponding consequences. With this theoretical foundation established, the next chapter endeavors to translate these described characteristics in order to empirically test them within a specific case context.

3 Methodology

Section 3.1 delves into the Evolutionary Multi-Objective Direct Policy Search (EMODPS), the optimization framework employed in this study. While this thesis primarily focuses on theory-building, a case study serves as a methodological tool, playing a supportive role. Section 3.2 provides a detailed overview of the chosen case, the Eastern Nile River Basin, and its associated model. These methodological foundations lay the groundwork for result generation, as elaborated in the Experimental Setup described in Section 3.3.

3.1. Evolutionary Multi-Objective Direct Policy Search

Resevoir management optimization models are, due to their high-dimensionality, very fit to be constructed with Evolutionary Multi-Objective Direct Policy Search (EMODPS) as the fundamental approach. In essence, it involves integrating a nonlinear approximating network as a policy function into a simulation model. This function calculates release decisions at each time step based on the system's state at that specific instance. Throughout the optimization process, the parameters of the policy function are refined in each generation of a Multi-Objective Evolutionary Algorithm (MOEA) run (Giuliani et al., 2016). In an ideal scenario, the solution set converges to the Pareto Frontier for the set of objectives. Pareto-optimality theory posits that a solution is Pareto-optimal if there is no other solution that could improve one objective without worsening another (Pareto, 1906). Figure 3.1 provides a visual summary of the EMODPS methodology implemented on the XLRM framework.

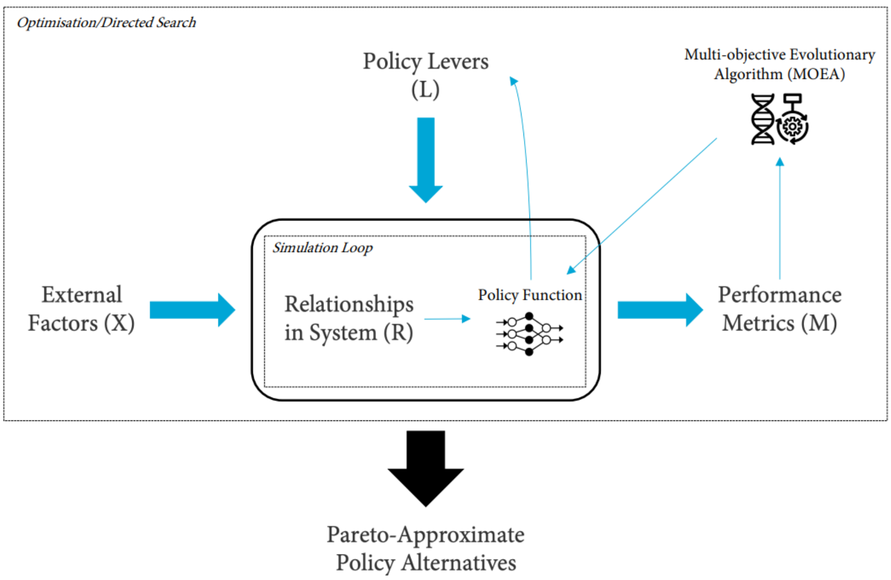


Figure 3.1: Schematization of the EMODPS framework on top of the XLRM framework.

3.1.1. Epsilon Non-dominated Sorting Genetic Algorithm

Figure 3.1 illustrates that in implementing the Evolutionary Multi-Objective Direct Policy Search (EMODPS) framework, a MOEA serves as a crucial building block. The selected MOEA for this study is Epsilon Non-dominated Sorting Genetic Algorithm II (ε-NSGAII), and this section will elaborate on why this evolutionary algorithm is well-suited and provide insights into its characteristics.

Rationale for Selecting ε-NSGAII

The nature of this study involves simultaneous optimization of several conflicting objectives, a characteristic of many-objective optimization problems. Traditional optimization methods are unsuitable for this research due to their inability to handle multiple conflicting objectives without converting the multi-objective optimization problem to a single-objective optimization problem by emphasizing one particular Pareto-optimal solution at a time (Chand and Wagner, 2015; Deb et al., 2002). Hence, a many-objective optimization algorithm is essential. The ε-NSGAII was selected as it is an effective and widely recognized algorithm for many-objective optimization problems, proven by (Zatarain Salazar et al., 2016). It is an extension of the Non-dominated Sorting Genetic Algorithm II (NSGAII) (Deb et al., 2002), enhanced by Deb and Jain (2013) with the concept of ε-dominance for addressing problems with a large number of objectives, providing a way to effectively compare and rank solutions in the objective space.

Brief Description of ε-NSGAII

The ε-NSGAII, a genetic algorithm incorporating selection, crossover, and mutation operators (Kollat and Reed, 2005; Jansen et al., 2001), initiates with a population of potential solutions. Through iterative selection, a mating pool is formed, with each solution represented by parameters and evaluated using a fitness function. Genetic operators create new solutions from the current population, with the process repeating until meeting a specified criterion. Notably, ε-dominance, a concept considering a solution superior if it is equal or superior in all objectives and better by at least a factor of ε in at least one objective, enhances computational efficiency (Deb and Jain, 2013). Appendix A.2 provides a comprehensive ε-NSGAII description, illustrated in Figure A.1, showcasing crossover, mutation, and non-dominated sorting for selecting optimal solutions.

To implement the ε-NSGAII algorithm, the Platypus library, an open-source Python library for multi-objective optimization, will be employed. Section 3.3.1 in the Experimental Setup contains the implementation plan with the configurations of the required algorithm parameters as the number of function evaluations, population size, crossover , and more. It is important to note that incorporating the principles of distributive justice A Priori into the study necessitates the translation of these principles into mathematical terms that can be integrated into the algorithm. This may entail the formulation of objective functions or the addition of constraints to the algorithm. This step is imperative as it ensures that the optimized solutions generated by the algorithm are not only Pareto-optimal but also align with the principles of distributive justice, thereby rendering them fair and just. Section 4.2 will dive will show what mathematical formulations are deemed fit.

3.2. Case-study: The Eastern Nile River Basin

The Nile River, with a total length of approximately 6,800 kilometers, stands as the longest river in the world(Said, 2012). This essential waterway is a lifeline through northeast Africa for its riparian countries. The eleven nations depend on the recourse for hydro-power, municipal, industrial, and agricultural consumption (NBI, 2023). There have been debates for years over the right to extract water from the Nile. Political tensions are particularly palpable in the eastern part of the basin, since from all players Egypt has exploited the water the most (Swain, 2002).The Grand Ethiopian Renaissance Dam (GERD), Ethiopia's Hydro-power project which started in 2011, has increasingly challenged Egypt's water hegemony, though Ethiopia claims its aim is to unlock hydro-power potential (Negm et al., 2018). The GERD has brought political and technical complexities to the management of the Nile system and has raised concerns among downstream countries about their water security.

The river is known for its water inflow variability, marked by frequent drought and flood events. The escalating populations and economic production in the region signal an increasing demand for water (Abu-Zeid and Biswas, 1991; Taye et al., 2015). Consequently, the design of operating policies for reservoirs in the basin becomes a complex issue that necessitates consideration of physical infrastructure, geopolitics, socioeconomic factors, and hydro-climatic uncertainties. The Eastern Nile River Basin (ENRB), depicted geographically in Figure 3.2, stands out as a highly studied case. Research on the ENRB encompasses various aspects, such as cooperation (Mason, 2004), optimal filling strategies for the new GERD (Wheeler et al., 2016), and more. However, in the context of this research focusing on Distributive Justice, it is crucial to comprehend the current state of the system.

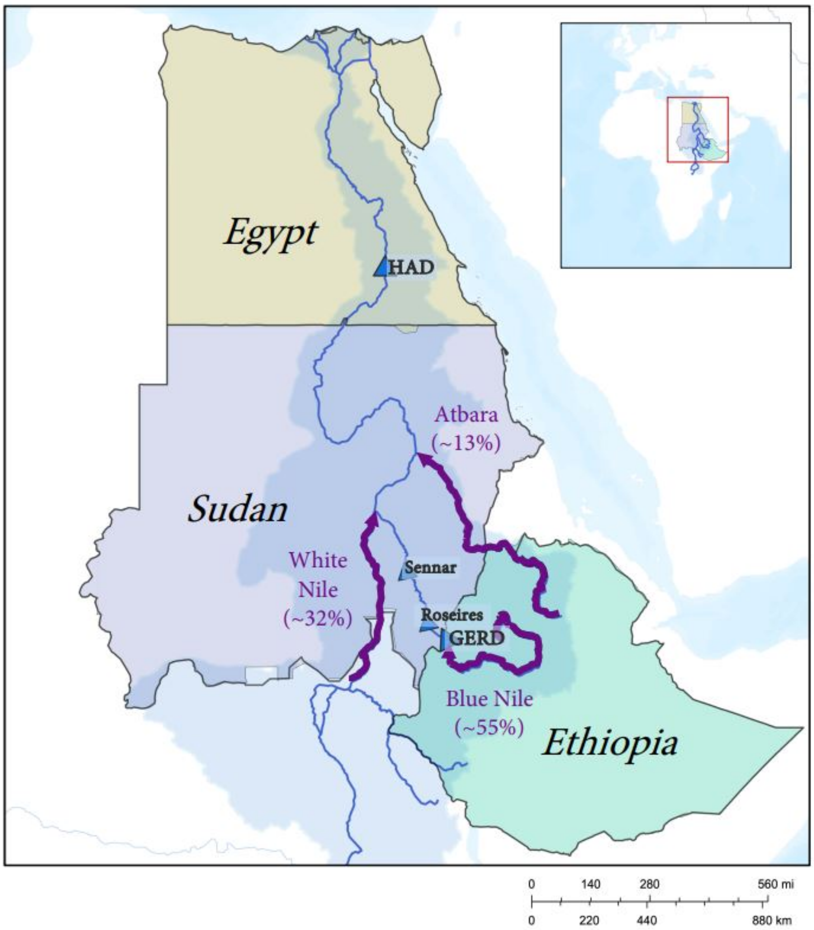


Figure 3.2: Eastern Nile River Basin with the percentile contribution of the three main tributaries (Blue Nile, White Nile and Atbara) and the three riparian countries (Ethiopia, Sudan, and Egypt), from Sari (2022).

The geographical summary of the Eastern Nile Basin is depicted in figure 3.2. The Nile's total annual flow is primarily sourced from three main tributaries: the White Nile, the Blue Nile, and the Atbara rivers Talbot and Williams (2009). The White Nile, originating from Uganda's Lake Victoria, contributes approximately 32% to the main flow, offering stability across seasons (Wheeler et al., 2020). On the other hand, the Blue Nile and Atbara rivers, both originating in the Ethiopian highlands, contribute approximately 55% and 13%, respectively, with highly seasonal flows due to the variability of rainfall in the Ethiopian highlands (Wheeler et al., 2020).

3.2.1. Contextualizing ENRB Water Resource Utilization

The introductory section underscored the trans-boundary nature of the water system in the Eastern Nile River Basin (ENRB). Despite the shared water resource among the three primary riparian countries, namely Ethiopia, Sudan, and Egypt, each nation utilizes the water in distinctive ways (Goor et al., 2010). While countries use water in a wide variety of ways, the main exploitation of the resource is what guides political intents (Gleick and Heberger, 2014). The different main ways of exploitation are shown in figure 3.3. Ethiopia relies on the Nile for electricity generation (Arsano and Tamrat, 2005), while Sudan's economy is predominantly agricultural, with various irrigation districts sourcing water from the river for their crops (Hamad and El-Battahani, 2005). In Egypt, a notably arid nation, the Nile serves as a vital source for both domestic consumption and agricultural requirements (Hefny and Amer, 2005). The different actor perspectives are discussed in more detail in A.1. This divergence in water usage highlights their unique objectives, yet simultaneously the trans-boundary nature underscores a significant inter-dependency among these nations for realizing these objectives (SWAIN, 1997).

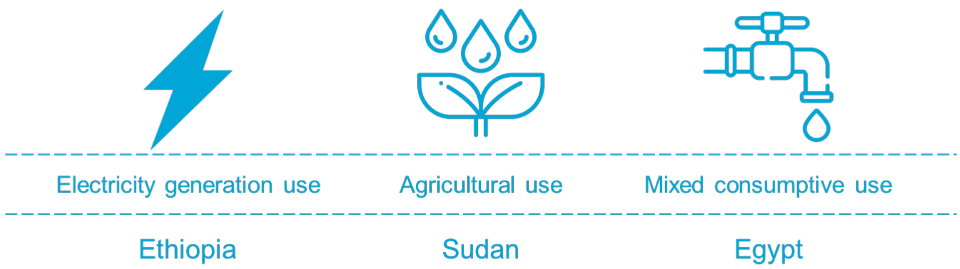


Figure 3.3: The different main uses of the water resource per country.

Climate change further exacerbates these intricate hydro-political issues, with projections indicating a potential 2.0°C to 4.0°C rise in mean annual temperature and uncertain precipitation changes ranging from -12% to +24% projected for 2050 (Hasan et al., 2018). Figure 3.4 draws how climate change's impact isn't uniform; different regions within these countries will experience varied hydro-climatic shifts. This further destabilizes the numerous agreements and pacts for water-management in the ENRB (Crabitès, 1929; Abdalla, 1971; Salman, 2013). The trans-boundary aspect, inter-dependency, climate-change effects all show the importance of distributive justice for water-management in the ENRB, making this a fitting case for this research.

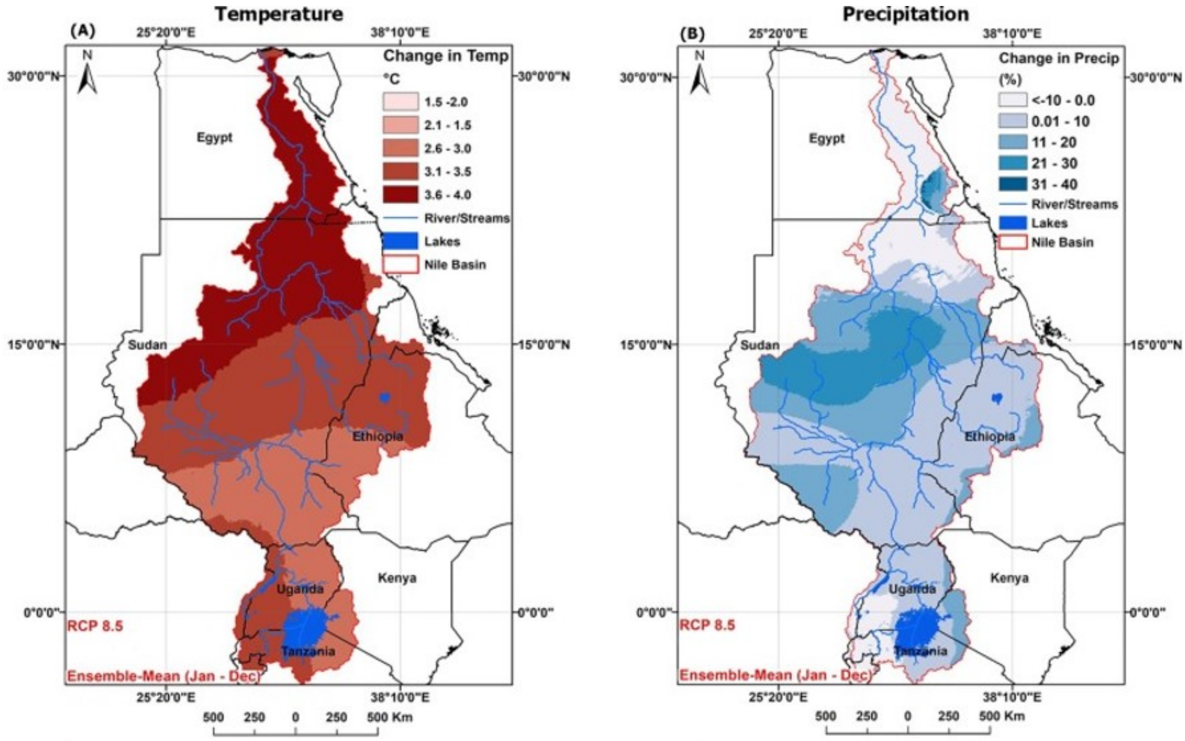


Figure 3.4: Future changes in temperature (A) and precipitation (B) for the year 2050 using ensemble mean of 17 GCMs for RCP 8.5 emission scenario with changes calculated relative to baseline (1960–1990), from Hasan et al. (2018).

3.2.2. The ENRB Model

For managing the Eastern Nile River Basin and its complex interplay of socio-economic and hydrological dynamics, a robust analytical tool becomes imperative. This section introduces the Simulation Model, slightly adjusted from (Sari, 2022), designed to unravel the multifaceted interactions within the basin. The model is built in Python using object-oriented programming. This is a programming paradigm that organizes code around ”objects” entities that perform computations and save local state, combining the properties of procedures and data (Stefik and Bobrow, 1985). This section provides an in-depth exploration of the model’s architecture and functionalities, ensuring the reproducibility of results for future analyses.

Model Scope

The Space Demarcation focuses on the Blue Nile, which significantly contributes to the Nile’s total flow and houses the GERD, a central focus of this study. The White Nile and Atbara rivers are treated as external streamflows, their dynamics excluded from simulation but incorporated as time-series inputs. The simulation initiates with the Blue Nile’s inflow to the GERD upstream, concluding by consolidating Egypt’s water demand as a singular demand zone served by the HAD downstream.

The Temporal Demarcation spans 20 years, from 2022 to 2042. This time-frame is pivotal for encompassing the GERD’s filling period and enabling thorough observation of potential trade-offs during its operational phase.

The Recipient Demarcation defines the beneficiaries of benefits or burdens arising from the current state and analyzed policies. The focus lays with the three countries: Ethiopia, Sudan, and Egypt. Further demarcation considers the distribution of benefits based on each country’s primary use and specified objectives. Table 3.1 illustrates the model’s incorporated objectives, delineating distinct stakeholders within the same river basin system. This characterization aligns this study as an intra-generational analysis. Given the relatively short simulation horizon, the study does not extend its gaze to future generations as recipients of benefits or burdens, thereby excluding an intergenerational dimension.

Countries	Objectives	Aggregation level	Unit	Direction of Optimization
Egypt	Irrigation Demand Deficit ratio	Yearly average	-	Minimize
	Irrigation Demand Deficit ratio	90^{th} percentile worst month	-	Minimize
	HAD Level Deficit ratio	Frequency over 20 years	-	Minimize
Sudan	Irrigation Demand Deficit ratio	Yearly average	-	Minimize
	Irrigation Demand Deficit ratio	90^{th} percentile worst month	-	Minimize
Ethiopia	Hydro-power Demand Deficit ratio	Yearly average	-	Minimize

Table 3.1: The model objectives per country.

Model Setup

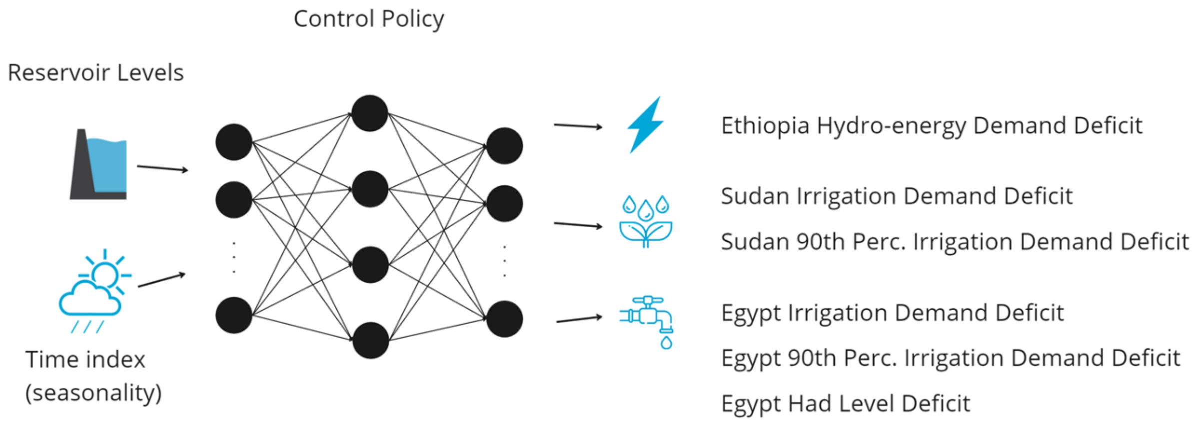
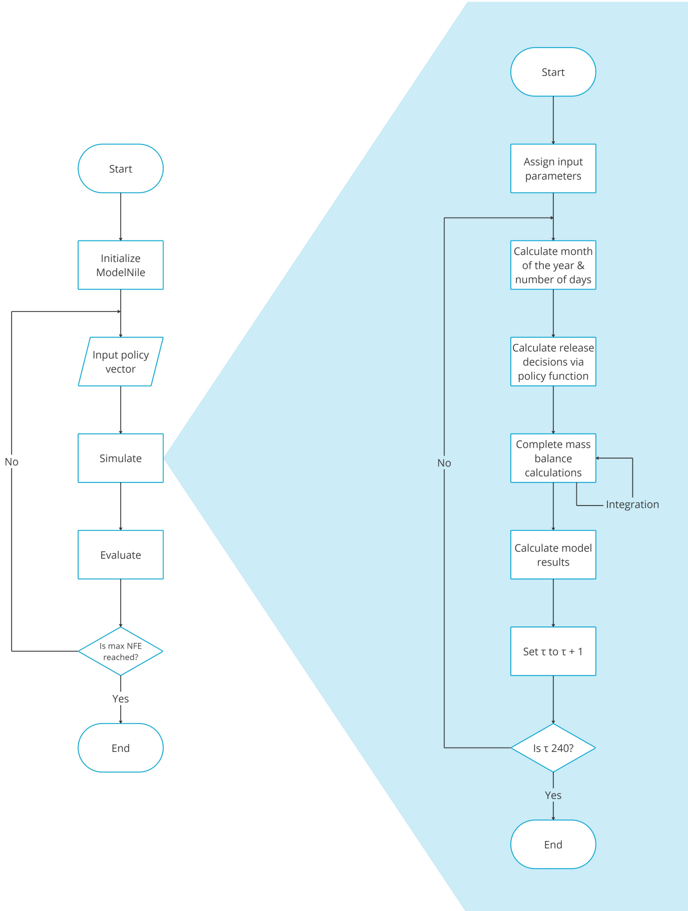
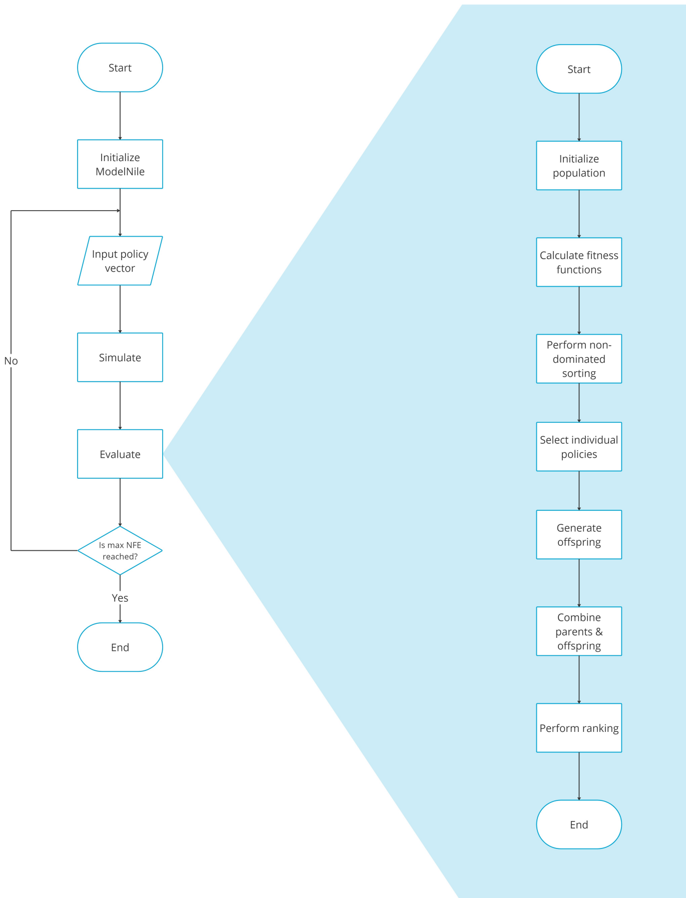


Figure 3.5: Visualization of reservoir levels and time index as inputs for creating an ENRB control policy, consisting of radial basis functions. These functions determine the corresponding release decisions, which are designed to meet the different country objectives for Ethiopia, Sudan, and Egypt. The visualization is a for the ENRB adapted version of the control policy illustration by Zatarain Salazar et al. (2016).

The model scope in combination with the 3.1 framework lead to forming of control policies as schematized in figure 3.5. The intricate workings of the model are encapsulated step-by-step in the flowcharts depicted in Figure 3.6. Divided into two pivotal components—Simulation and Evaluation—the model employs a systematic approach to comprehend model components. The simulation phase, illustrated in sub-figure 3.6a, captures the diverse factors influencing the Eastern Nile's hydrological dynamics. Subsequently, the evaluation phase, presented in sub-figure 3.6b, assesses the simulated outcomes against predefined criteria. This model serves as a basis, allowing us to later adapt the model and explore the impact of evaluating the model outcomes with the Distributive Justice principles.



(a) Simulation



(b) Evaluation

Figure 3.6: The model flowchart with sub-flowcharts providing a zoom in on the simulation (a) and evaluation (b) steps.

3.3. Experimental Setup

The previous section described how the model simulates and subsequently evaluates using the model objectives. In this research Distributive Justice if enforced by using the principles of Distributive Justice described in chapter 2 as evaluation metrics. These metrics are passed as an additional objective in the evaluation process described in figure 3.6b. Table 3.2 shows the new complete overview of all the objectives used for optimization. With these objectives different problem formulations are specified for each experiment. This process is described in the following section.

Countries	Objectives	Aggregation level	Unit	Direction of Optimization
Egypt	Irrigation Demand Deficit ratio	Yearly average	-	Minimize
	Irrigation Demand Deficit ratio	90^{th} percentile worst month	-	Minimize
	HAD Level Deficit ratio	Frequency over 20 years	-	Minimize
Sudan	Irrigation Demand Deficit ratio	Yearly average	-	Minimize
	Irrigation Demand Deficit ratio	90^{th} percentile worst month	-	Minimize
Ethiopia	Hydro-power Demand Deficit ratio	Yearly average	-	Minimize
All	Utilitarian Social Welfare	All country objectives	-	Maximize
All	Egalitarian Social Welfare	All country objectives	-	Maximize
All	Prioritarian Social Welfare	All country objectives	-	Maximize

Table 3.2: The model objectives containing the added Distributive Justice objectives.

The aim of this research is not only to evaluate Distributive Justice, but also to compare an A Priori approach for this with an A Posteriori approach. Table 3.3 in the first column shows an overview of the needed four experiments to make such a comparison. The optimization is run for a reference problem formulation, and three distributive justice principle problem formulations. Each optimization is post-processed to calculate the A Posteriori distributive justice results of the problem formulations that are not used for optimization within that experiment.

Experiment	Reference Problem Formulation	Utilitarian Problem Formulation	Egalitarian Problem Formulation	Prioritarian Problem Formulation
Reference	A Priori	A Posteriori	A Posteriori	A Posteriori
Utilitarian	A Priori	A Priori	A Posteriori	A Posteriori
Egalitarian	A Priori	A Posteriori	A Priori	A Priori
Prioritarian	A Priori	A Posteriori	A Posteriori	A Priori

Table 3.3: The Experimental Design highlighting in blue the used problem formulations in-processing(A Priori), and labeling the used problem formulations for evaluating post-processing (A Posteriori).

3.3.1. General Configurations

The Number of Function Evaluations refers to the frequency at which the EMODPS model is executed. The optimization process undergoes updates following each function evaluation. Consequently, tracking the number of function evaluations serves as an indicator of the optimization's convergence, signifying the stability of the solutions. In the context of the EMODPS utilizing the ε-NSGAII algorithm to approximate the Pareto front, stability denotes a state where the Pareto front approximation remains relatively consistent across successive model runs.Increasing the number of function evaluations enhances the likelihood of solutions converging towards the true Pareto front.

In the prior study of Sari (2022), 50,000 function evaluations were employed, resulting in observed convergence in solutions. However, given the model adjustments made, we monitor various convergence metrics to assess if this number remains adequate. An explanations of these metrics can be found in Appendix B.3.

Seeds play a crucial role in determining the initial points of the system state for simulation. This is due to the fact that the ε-NSGAII algorithm, employed to conduct the EMODPS model simulation, incorporates stochasticity to sample potential solutions. This renders the solutions sensitive to the selected seed. Although these seeds are termed "random," they are generated through pseudo-random sequences, which are deterministic and non-random in nature. Consequently, the solutions obtained are contingent upon these pseudo-random sequences.

To mitigate this dependency on the pseudo-random behavior, a random seed analysis was conducted. This analysis helps control the unforeseen effects of variability and enhances consistency across multiple runs. The model is configured for five seeds per experiment. Appendix B.3.1 delves into the verification process, assessing the model's behavior under varied seed conditions and evaluating the sufficiency of this selected number.

4

Analysis

The model flowchart depicted in Figure 3.6 comprises two primary modeling blocks: the simulation step and the evaluation step. This chapter initially presents the equations essential for conducting computations in the simulation step. Subsequently, a clear distinction is provided between the equations employed to evaluate the model outcomes using a reference problem formulation and those utilized for evaluating Distributive Justice in a distinct problem formulation.

4.1. Equations used for Simulation

$$u_\tau^k = \sum_i \left[w_i^k \varphi_i \left(S_\tau, \sum_p Q_{\tau-1}^p, \tau \bmod 12 \right) + \alpha_k \right] \tag{4.1}$$

Equation 4.1 details the computation of the release decision (u_τ^k), which is a weighted, (w_i^k), sum of the Radial Basis Function (RBF) at every index level, (φ_i) adjusted with a constant adjustment parameter (α_k). This calculation occurs at the onset of each month (τ) for every reservoir (k). The equation provides insight into the specific inputs utilized by the policy function, representing the system's state at a given moment.

The first input, denoted as S_τ, forms a vector containing the storage values for all reservoirs. The second input, $(\sum_p Q_{\tau-1}^p)$, corresponds to the cumulative catchment inflows, representing the overall system gain, in the preceding month. Additionally, the policy function considers the current month of the year $(\tau \bmod 12)$ as an input, addressing seasonal variations before determining the release strategy.

$$s_{\tau+1}^k = s_\tau^k + \int_0^1 f\left(s_{\tau+t}^k, q_\tau^k, e_{\tau,}^k, u_\tau^k\right) dt \tag{4.2}$$

For which:

$$f = \frac{\Delta s_{\tau+t}^k}{\Delta t} = \underbrace{q_\tau^k}_{\text{net inflow}} - \underbrace{A^k\left(s_{\tau+t}^k\right) e_\tau^k}_{\text{evaporation}} - \underbrace{r^k\left(s_{\tau+t,}^k u_\tau^k\right)}_{\text{actual release}} \tag{4.3}$$

And:

$$r^k\left(s_{\tau+t}^k, u_\tau^k\right) = \begin{cases} \overline{r^k}\left(s_{\tau+t}^k\right), & \text{if } u_\tau^k > \overline{r^k}\left(s_{\tau+t}^k\right) \\ \underline{r^k}\left(s_{\tau+t}^k\right), & \text{if } u_\tau^k < \underline{r}^k\left(s_{\tau+t}^k\right) \\ u_\tau^k, & \text{otherwise} \end{cases} \tag{4.4}$$

Equation 4.2 provides a broad overview of the variation in storage for reservoir k when transitioning from month τ to $\tau + 1$. Precise calculations of evaporation and release values are dynamically derived based on the most current storage values within a given month. These values are then integrated over time to ascertain the overall addition to or deduction from reservoir storage.

The integration function, f, takes into account the most recent storage value $(s_{\tau+t}^{k})$, along with inputs such as net inflow (q_{τ}^{k}), evaporation rate $(e_{\tau,}^{k})$, and the release decision (u_{τ}^{k}) from equation 4.1. Three elements contribute to the in-month change in reservoir storage depicted in equation 4.3. The net inflow (q_{τ}^{k}) represents the water flow per second received from the model components preceding reservoir k in the model topology. The function converting reservoir storage to the corresponding surface area $(A^{k}(s))$ is then multiplied by the evaporation rate of the month (e_{τ}^{k}), determining the water loss due to evaporation per second. The final component is the actual release $(r^{k}(s_{\tau+t}^{k}, u_{\tau}^{k}))$, for which equation 4.4 is the full form. The release is bounded considering the constraints imposed by the reservoir characteristics. The actual release is confined within the minimum and maximum allowable releases, $(\underline{r^{k}})$ and $(\overline{r^{k}})$, determined by the storage (S) in the reservoir at the given time instance. For a more in-depth overview into the input-output relations of the these model components, refer to Sari (2022).

4.2. Equations used for Evaluation

With the model results from the simulation created using the equations in section 4.1 the Evolutionary Algorithm (EA) can try to approach the Pareto approximate set using the problem formulations posed in this section. These problem formulations are implemented in the model as objective functions that are either minimized or maximized by the EA.

4.2.1. Reference Problem Formulation

In this section, we dissect the set of objective functions, distinguished in blue, that serve as the problem formulations for the Reference Experiment, as depicted in Figure 3.3. Equations not highlighted in blue are provided for explanatory purposes. Each objective signifies a deficit ratio, with all units denoted in percentages. For instance, a value of 0.2 indicates a demand deficit equivalent to 20% of the overall demand. The goal for all formulations is to minimize these deficit ratios.
The first objective function, equation 4.5, represents the *Egypt Average Yearly Irrigation Demand Deficit*. It calculates the deficit ratio for each time step τ by taking the maximum of 0 and the difference between the demand (D_{τ}^{Egypt}) and available water (V_{τ}^{Egypt}), normalized by the demand.

$$Egypt\ Average\ Yearly\ Irrigation\ Demand\ Deficit = \frac{1}{20}\sum_{\tau=1}^{240} \max\left(0, \frac{D_{\tau}^{Egypt} - V_{\tau}^{Egypt}}{D_{\tau}^{Egypt}}\right) \tag{4.5}$$

The *Egypt* 90^{th} *Percentile Worst Demand Deficit* is determined by selecting the 90^{th} percentile of the calculated monthly deficits. It uses the same max function as in equation 4.5.

$$Egypt\ 90^{th}\ Percentile\ Worst\ Demand\ Deficit = Percentile\left(\left\{\max\left(0, \frac{D_{\tau}^{Egypt} - V_{\tau}^{Egypt}}{D_{\tau}^{Egypt}}\right) \mid \tau = 1, 2, \ldots, 240\right\}, 90\%\right) \tag{4.6}$$

Equations 4.7 and 4.8 collectively constitute the *Egypt HAD Level Deficit*. This objective function is derived by tallying the instances where the HAD level falls below a predetermined threshold throughout the simulation period. The tallying function HAD_{τ} is a binary function indicating whether the HAD level $(h_{HAD}(s_{\tau}))$ is less than the threshold value of 159. To ensure a normalized representation, the count is divided by the duration of the simulation.

$$Sudan\ Had\ Level\ Deficit = \frac{1}{240}\sum_{\tau=1}^{240} HAD_{\tau} \tag{4.7}$$

$$HAD_{\tau} = \begin{cases} 1, & \text{if } h_{HAD}(s_{\tau}) < 159 \\ 0, & \text{otherwise} \end{cases} \tag{4.8}$$

Similarly to Equation 4.5, Equation 4.9 calculates the *Sudan Average Yearly Irrigation Demand Deficit*. However, in contrast to a singular value for the entire country, this equation accounts for the diverse irrigation needs across different districts, denoted by $(j \in SD)$. The computation involves determining the deficit for each specific district and aggregating these individual deficits to provide an overall measure for Sudan's irrigation demand shortfall.

$$Sudan\ Average\ Yearly\ Irrigation\ Demand\ Deficit = \frac{1}{20}\sum_{\tau=1}^{240}\sum_{j\in SD}\max\left(0, \frac{D_\tau^j - V_\tau^j}{D_\tau^j}\right) \tag{4.9}$$

The *Sudan* 90^{th} *Percentile Worst Demand Deficit*, equation 4.10, calculates the 90^{th} percentile of the monthly deficits for all sub-districts in Sudan, using the max function.

$$Sudan\ 90^{th}\ Percentile\ Worst\ Demand\ Deficit = Percentile\left(\left\{\sum_{j\in SD}\max\left(0, \frac{D_\tau^j - V_\tau^j}{D_\tau^j}\right) \mid \tau = 1, 2, \ldots, 240\right\}, 90\%\right) \tag{4.10}$$

The *Ethiopia Hydropower Demand Deficit* is determined by subtracting the generated hydropower, which is the power output of the plant (P_{GERD}^τ) times the hours in the current month $(d(\tau \mod 12)\cdot 24)$, from the required hydropower $(D^(Ethiopia)$. It considers the GERD power output and the duration of power generation for each month.

$$Ethiopia\ Hydropower\ Demand\ Deficit = \frac{1}{20}\sum_{\tau=1}^{240}\frac{D^{Ethiopia} - P_{GERD}^\tau \cdot d(\tau \mod 12)\cdot 24}{D^{Ethiopia}} \tag{4.11}$$

The GERD Power Generation from equation 4.11 is further decomposed in the following equation. The value is based on the minimum of the GERD release and the maximum release, a gravitational constant (g), the difference in reservoir levels, and the efficiency factor (η_G).

$$P_\tau^{GERD} = \min(r_\tau^{GERD}, \overline{r^{GERD}})\cdot g\cdot \max(0, h^{GERD}(s_\tau) - h_{turbine}^{GERD})\cdot \eta_G \tag{4.12}$$

Given that Ethiopia faces challenges in electricity access, with only 27% of the population connected to the grid (NBI, 2023), the demand for electricity generation is set at the maximum capacity of the GERD. This decision is made recognizing that even at this capacity, meeting the demand for every household remains unattainable. This leads to the formulation of the energy demand equation 4.13.

$$D^{Ethiopia} = \overline{PGERD_\tau}\cdot d(\tau \mod 12)\cdot 24 \tag{4.13}$$

Substituting this newly defined energy demand $(D^{Ethiopia})$ into equation 4.11 yields the final objective function equation 4.14.

$$Ethiopia\ Hydropower\ Demand\ Deficit = \frac{1}{20}\sum_{\tau=1}^{240}\frac{\overline{PGERD_\tau} - PGERD_\tau}{\overline{PGERD_\tau}} \tag{4.14}$$

4.2.2. Distributive Justice Problem Formulations

This section introduces three distinct approaches to assessing the distributive justice between the objectives presented in the previous section: Utilitarianism, Egalitarianism, and Prioritarianism. The corresponding social welfare functions (SWFs) are represented by Equations 4.15, 4.16, and 4.17. These SWFs are adapted versions of the formulas introduced in Chapter 2, tailored to suit the characteristics of the case model. The Utilitarian problem formulation, embodied in Equation 4.15, strives to maximize overall well-being by aggregating the utility (u_{ij}) of all objectives (j) for each country (i).

$$Utilitarian\ Social\ Welfare = \sum_{i=0}^{n}\sum_{j=0}^{n} u_j^i \tag{4.15}$$

The Egalitarian problem formulation, as encapsulated in Equation 4.16, evaluates justice by calculating the absolute differences in utility between pairs of individuals, considering variations in utility across all objectives of all countries. This formulation resembles the Gini-index as shown in equation 2.3.

$$Egalitarian\ Social\ Welfare = \frac{\sum_{j=0}^{n} \sum_{j=0}^{n} \left| u_i(x_i) - u_j(x_j) \right|}{2n^2 u_i(\bar{x}_i)} \tag{4.16}$$

The Prioritarian problem formulation assesses justice by considering the disparity in utility among individuals, with a specific emphasis on enhancing the well-being of those with lower utility values. In contrast to the Utilitarian problem formulation, Prioritarian utility is derived from the transformation function presented in Equation 4.18. This transformation function is an adapted version of the one in Equation 2.5, with the exclusion of w_{zero} in our model. This exclusion is justified as the objectives inherently involve deficits, eliminating the need for an additional zero base. The parameter γ in the equation determines the extent of priority assigned to individuals with lower utility.

$$Prioritarian\ Social\ Welfare = \sum_{i=0}^{n} \sum_{j=0}^{n} g(u_j^i) \tag{4.17}$$

$$g(u_j^i) = \begin{cases} \frac{(u_{ij})^{1-\gamma}}{1-\gamma}, & \text{if } \gamma! = 1 \\ ln(u_{ij}), & \gamma = 1 \end{cases} \tag{4.18}$$

These formulations provide a comprehensive framework for evaluating the distributional justice implications of water allocation in the Eastern Nile River Basin. The subsequent sections detail the results obtained through these formulations, shedding light on the trade-offs and considerations within the studied system.

5
Results

This chapter showcases the effects of incorporating a Utilitarian, Egalitarian and Prioritarion Problem Formulation in MOO by conducting the analysis described in chapter 4. The initial section presents the outcomes of the Reference Experiment, serving as an introduction to the subsequent analyses. Additionally, this section provides guidance on interpreting parallel coordinates plots, a multidimensional data visualization method employed in this study, where each data point is represented by a line connecting values on parallel axes. Table 5.1 contains a comprehensive overview of these axes and their respective content. Subsequently, a comparative analysis is performed, comparing the results of the Reference Experiment with the results observed during A Posteriori evaluation using the three problem formulations. This is followed by a section that showcases the effects of a A priori incorporation of the added problem formulations. Finally, the A Posteriori and A Priori methods are compared.

Axis Name	Objectives	Unit	Direction of Optimization	Aggregation Level	Countries
Egypt Irr. Deficit	Irrigation Demand Deficit ratio	-	Minimize	Yearly average	Egypt
Egypt 90^{th} Irr. Deficit	Irrigation Demand Deficit ratio	-	Minimize	90^{th} percentile worst month	Egypt
Egypt HAD Level Deficit	HAD Level Deficit ratio	-	Minimize	Frequency over 20 years	Egypt
Sudan Irr. Deficit	Irrigation Demand Deficit ratio	-	Minimize	Yearly average	Sudan
Sudan 90^{th} Irr. Deficit	Irrigation Demand Deficit ratio	-	Minimize	90^{th} percentile worst month	Sudan
Ethiopia HP Deficit	Hydro-power Demand Deficit ratio	-	Minimize	Yearly average	Ethiopia
Utilitarian	Utilitarian Social Welfare	-	Maximize	All country objectives	All
Prioritarian	Egalitarian Social Welfare	-	Maximize	All country objectives	All
Egalitarian	Prioritarian Social Welfare	-	Maximize	All country objectives	All

Table 5.1: Details for every axis used for solution space visualization in the chapter Parallel Coordinates plots.

5.1. The Results of Reference Experiment

As illustrated in table 3.3, the Reference Experiment involves optimizing the six original objectives identified for the Eastern Nile River Basin case, constituting the reference problem formulation. This optimization process produced a Pareto approximate set comprising 207 solutions. Appendix B.3.1 offers a detailed convergence analysis for the various seed runs conducted to generate the presented solutions. Given the high-dimensionality of the data, parallel coordinates plots will be employed in this chapter to delve into the results and emphasize insights. These plots excel in capturing the relationships and patterns in multivariate data by depicting each solution as a connected line in a coordinate system of objective values, making them particularly useful for revealing trade-offs between the objectives considered in each problem formulation Inselberg and Dimsdale (1991). Figure 5.1 specifically showcases the parallel coordinates plot for the Reference Experiment. The plot (Figure 5.1) offers an initial exploration, providing a foundational understanding of ENRB model. It also serves as guidance for interpreting such plots before introducing added complexities with additional distributive justice problem formulations.

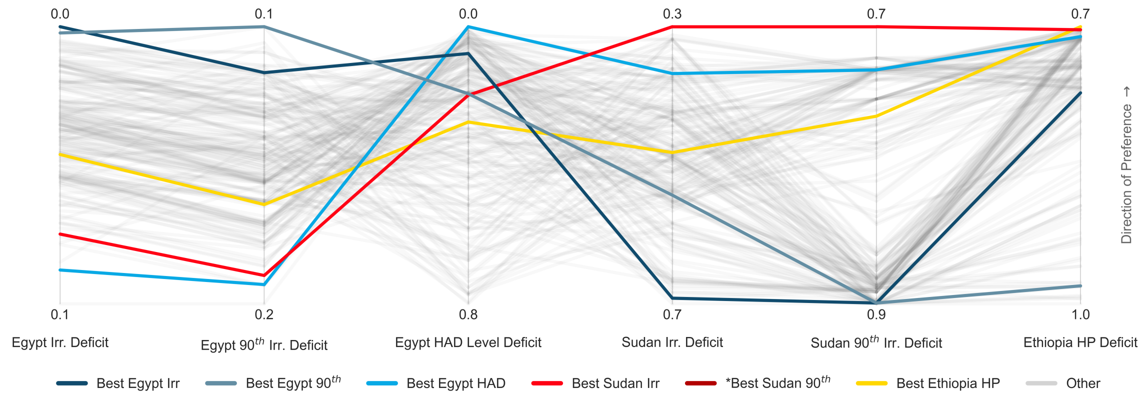


Figure 5.1: Parallel Coordinate Plots of the Pareto approximate set for the Reference Experiment. The colored lines show the single best solution for each objective. if not overplotted due to multiple objectives having the same best solution. * Best Sudan 90^{th} overplotted by Best Sudan Irr.

In the above figure, each axis represents the range of solution scores for a single objective. As elaborated in more detail in Table 3.1, the objectives are framed in deficits, signifying that, for example, a range of 0.0-0.1 corresponds to a deficit ranging from 0% to 10% relative to the overall demand for the respective good. The direction of preference, indicated on the right side of the plot, signifies that values on the top of the axes are favorable. Given that the model defines objectives as deficits, it is expected that, for all objectives, lower values appear at the top and higher values at the bottom. Each line represents a solution from the Pareto Approximate solution set for the experiment. When lines cross, this indicates that for that solution a trade-off is encountered between the objectives depicted on those axes. Six specific solutions, referred to as policies, are color-coded. A policy labeled with ”best” corresponds to the one yielding the most desirable value for the respective objective. Overlapping may occur when one policy scores the best on multiple solutions, resulting in some label colors not being visible in the figure. To identify the solution best for a particular objective, observe the color of the solution at the top of the axis of interest. In cases of overplotting, labels are marked with ”*” in their names and a figure note is added.

Reading the plots in the way described above, three significant trade-off patterns can be identified. The first of which involves the trade-off for the best irrigation policy for Egypt and Egypt's 90th percentile irrigation policy, both reds, with the objectives of the two other countries. A closer examination reveals that securing the irrigation deficit, while crucial for Egypt, may encounter resistance from mainly Sudan, as the best irrigation policy is the lowest-scoring for Sudan's two objectives. On the other hand, securing Egypt's 90th percentile worst month has even more complications since this objective also scores at the bottom range of all solutions for Ethiopia's Hydro-power generation.

The second trade-off pertains to Egypt's HAD level reliability, primarily constituting an internal issue as it involves a trade-off with the other two Egyptian objectives. The best policy for HAD level reliability, highlighted in bright-blue, while creating conflict within its country's objectives scores relatively high on objectives from other countries.

In contrast, Ethiopia's desired policy, yellow, exhibits a relatively steady level across all objectives, presenting a window of opportunity for cooperation. This steady policy profile allows for a cooperative approach, fostering collaboration with other countries in the region. Until now the model is analyzed by all the isolated objectives. Evaluating the model with an added layer of Distributive Justice objectives could show new trade-off patterns. Whether this is the case when evaluating Distributive Justice for the ENRB case is answered in the following section.

5.2. The Results of the A Posteriori Experiments

The functions presented in Section 4.2.1 of the analysis chapter are utilized for A Posteriori evaluation of the solutions obtained through optimization using the reference problem formulation. These functions, representing Utilitarian, Prioritarian, and Egalitarian evaluation metrics, serve as fairness metrics for scoring the solutions. The resulting scores are incorporated as three additional axes in the previously shown parallel coordinates plot for just the Reference Problem Formulation depicted in Figure 5.1, creating a comprehensive trade-off overview in Figure 5.2.The Utilitarian axis captures the aggregated value for the A Priori incorporated objectives of each solution, represented as a summation. Similarly, the Prioritarian values entail a summation, albeit of transformed utility values. This transformation creates very low aggregate utilities for some solutions that are very un-Prioritarian, hence the shift in range. The final axis, the Egalitarian scores, shows the Gini coefficient for each solution. A value closer to 0 signifies a more equitable distribution of the corresponding metric among the solutions, while a higher Gini coefficient indicates a greater degree of inequality or concentration of the metric across the solutions. Using the scores on these axes, also a new best solution is highlighted for each Distributive Justice objective. To distinguish between objectives used A Priori and those employed A Posteriori in post-processing, the A Priori objectives are highlighted with a light-blue box along the x-axis labels.

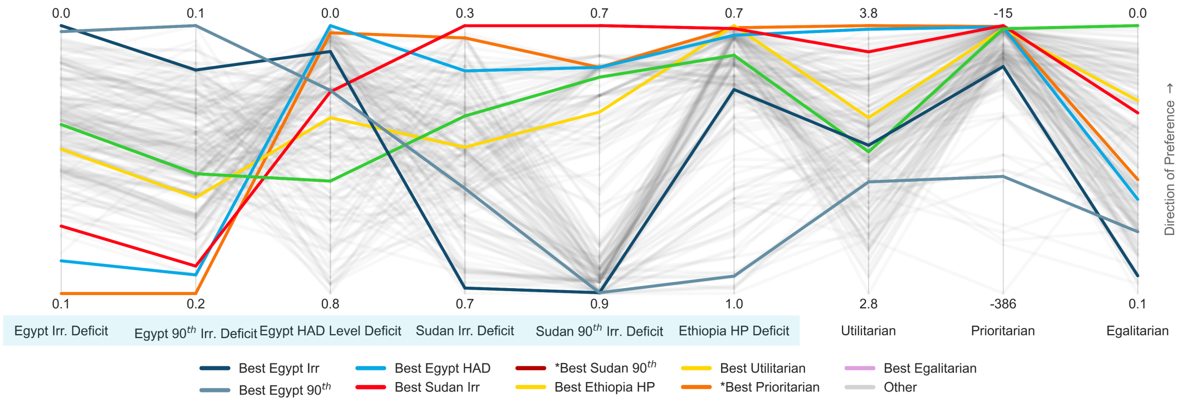


Figure 5.2: Parallel Coordinate Plots of the Pareto approximate set with A Posteriori evaluation of the Reference Experiment. The objectives used for A Priori optimization are highlighted by a light-blue box. The remainder non-highlighted objectives are used for A Posteriori Evaluation. The colored lines show the single best solution for each objective. * Best Sudan 90^{th} overplotted by Best Sudan Irr. * Best Prioritarian overplotted by Best Sudan Irr.

The main take-away from the plot is that the A Posteriori Evaluation does highlight other policies from the Pareto approximate set to be favorable than the policies highlighted by the previous objectives. Both the Utilitarian and Prioritarian best policies (colored in orange) exhibit an even more pronounced trade-off with the objectives of Egypt's Irrigation Deficit and Egypt's 90^{th} Irrigation Deficit. The green line, representing the best Egalitarian policy, introduces a new compromise solution. Compared to the previously identified compromise solution (Best Ethiopia Hydro-power), it is slightly less favorable for the Egypt Low HAD and Ethiopia Hydro-power objectives but scores higher for other objectives in Egypt and Sudan. This raises the question of whether there are additional solutions beyond the single best that share the same objective preferences, or if other solutions exhibit distinct trade-offs while adhering to the same principle. This idea is explored in figure 5.3 by highlighting the 10^{th} percentile of optimal solutions for the three Fairness Problem Formulations.

Before delving into the insights drawn from the plot, it is crucial to highlight a specific adjustment made in Figure 5.3. From now on the Prioritarian axis has been transformed into a ranked scale, where the solutions are mapped from most to least Prioritarian. This adjustment is necessary to enhance the distinguishability of the best solutions. It stems from the intentional skewness introduced by the transformation function explained in Section 2.2.3. The ranked version of Figure 5.2 with the adjusted Prioritarian axis also for that figure is presented in Appendix B.2.

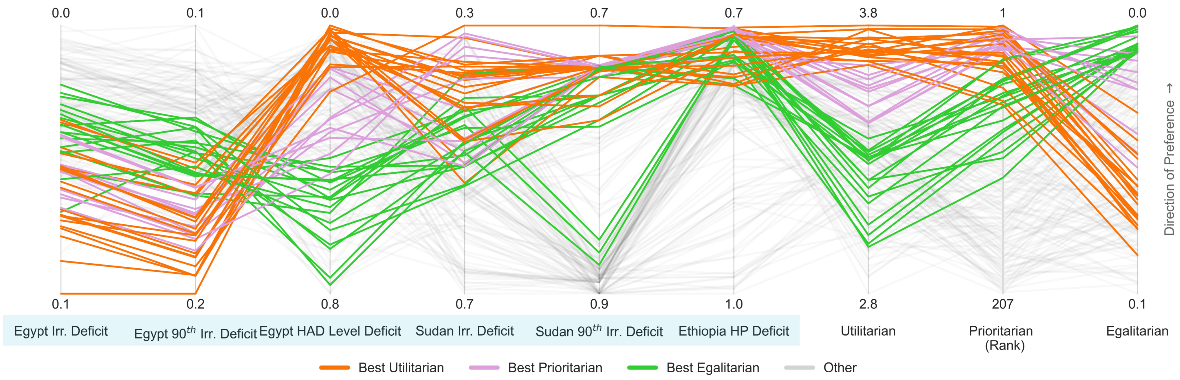


Figure 5.3: Parallel Coordinate Plots of the Pareto approximate set with A Posteriori evaluation of the Reference Experiment. The objectives used for A Priori optimization are highlighted by a light-blue box. The remainder non-highlighted objectives are used for A Posteriori Evaluation. The colored lines show the 10^th percentile best solution for the Utilitarian, Prioritarian (ranked) and Egalitarian Problem Formulations.

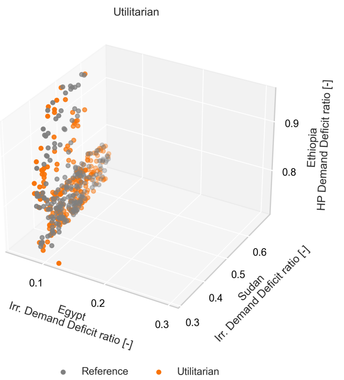
The plot reveals intriguing insights as we deviate from the single best solution towards the 10^{th} percentile of optimal solutions for the Fairness Problem Formulations. Distinct behaviors emerge among the principles. The non overplotted Best Prioritarian lines represent solutions uniquely identified through evaluation with these fairness formulations, providing valuable perspectives not captured by the other problem formulations. This metric prioritizes the Hydro-power Deficit of Ethiopia, since this is the most subordinate objective. This seems to mainly come at the cost of the HAD level deifcit for Egypt. The Irrigation Deficit of Sudan in some cased also benefits from this formulation compared to a Utilitarian perspective. Partly the same holds for the Best Egalitarian lines, only the effect is stronger for all the Egypt objectives, and the Sudan objectives don't benefit from this problem formulation.

Furthermore, the 10^{th} percentile of optimal solutions for the Fairness Problem Formulations exhibits distinctive patterns across various Reference Problem Formulation objectives. Notably, objectives such as Egypt Low HAD reveal separated ranges, indicating specific and concentrated solution preferences within this percentile. In contrast, objectives like Sudan Irrigation Deficit demonstrate a more dispersed distribution, suggesting a broader range of solutions within the same percentile. Finally, it can be concluded that Utilitarian and Egalitarian best solutions contain a strong trade-off in their preferences. These impacts on the desirable solutions underscores the significance of incorporating these problem formulations to uncover distinct and potentially favorable solutions.

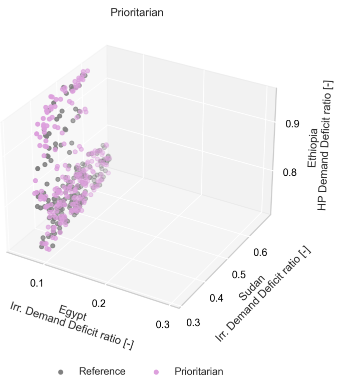
5.3. The Results of A Priori Experiments

Given the unique A Posteriori preferences highlighted in Section 5.1 for different Distributive Justice Problem Formulations. The subsequent exploration delves into the impact of these preferences on the optimization algorithm when utilizing the Fairness Problem Formulations for A Priori evaluation.

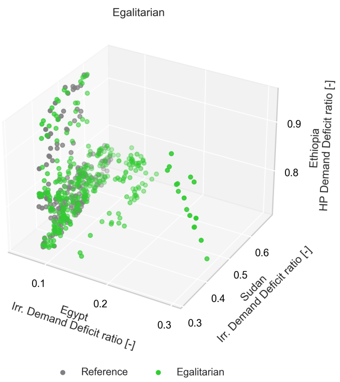
When globally analyzing the solution sets that result from the A Priori Utilitarian, Prioritarian and Egalitarian experiments, the Egalitarian Problem Formulation solely pushes the solution space to very new areas on the objective axes using the main deficit ratio for every country. This can be seen in figure 5.4 by the right area of the plot only containing solutions labeled Egalitarian. The Utilitarian and Prioritarian experiments do generate new solutions, but these are relatively close to the existing solutions for the Reference experiment.



(a) Utilitarian



(b) Prioritarian



(c) Egalitarian

Figure 5.4: The solution space for every experiment, which incorporates A Priori the Utilitarian, Prioritarian, or Egalitarian Problem Formulation, plotted using the main deficit ratio for every country (deficit/demand) on the axes.

A comprehensive view of a subset of the Pareto frontier is presented in figure 5.4, illustrating the shape by considering three out of the six objectives. Given the high dimensionality of the problem, a more detailed exploration of solution distribution across all axes is provided in Figure 5.5. This figure offers a thorough analysis of the ranges along each objective axis, providing a deeper insight into the spread of solutions across the entire multi-objective space.

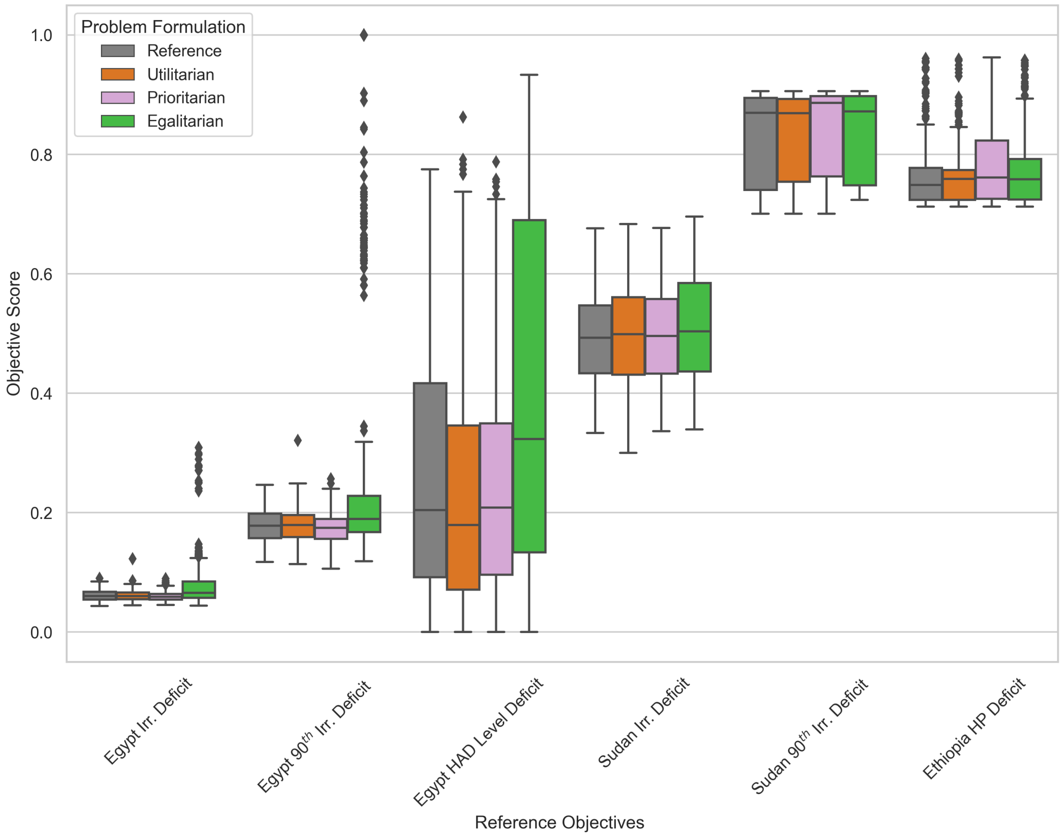


Figure 5.5: The Objective Value Ranges Reached for every A Priori Incorporation of a Problem Formulations.

The solution ranges vary based on the optimization formulation employed. Examining median values, it appears that only the water level deficits for the Egyptian HAD benefit from a Utilitarian formulation. In the Prioritarian case, the median values for subordinate objectives, namely Sudan's 90^{th} percentile and the Ethiopian Hydro-power objective, don't seem to gain advantages. Evidently, for the Egalitarian formulation, an attempt to level the playing field with the large Ethiopian deficit results in increased deficits for almost all objectives. Figures 5.4 and 5.5 considered the entire solution set. However, a refined analysis of a filtered subset allows for a detailed examination of specific trade-offs between objectives in selected policies. This approach provides insights into whether we observe new or different behavior compared to the previous broader analysis.

The Utilitarian Experiment, shown on the next page in subfigure 5.6b, found a Pareto approximate set of 219 solutions. Upon comparing the Reference experiment, sub-figure 5.6a, with the Utilitarian experiment, sub-figure 5.6b, three notable distinctions emerge. In the Pareto approximate set of Figure 5.6b, a novel optimal policy for the Sudan Irrigation Deficit becomes apparent. Additionally, the optimal Egypt HAD policy exhibits a more pronounced trade-off with the Sudan Irrigation Deficit objective, displaying a steeper trend compared to the set depicted in Figure 5.6a. Finally, the formerly best policy for the Egypt 90^{th} Irrigation Deficit is superseded in the new set.

Upon a detailed comparison of the 238 solutions presented in the Prioritarian Experiment, subfigure 5.6c, with the results from the first two subfigures, notable observations emerge. The optimal policy for the Sudan Irrigation Deficit once again exhibits a slight reduction, resembling the scenario observed in the Reference Experiment. However, a positive trend is identified for the Egypt Low HAD objective, as it still demonstrates improvements in this solution. It is noteworthy that the overall plot amalgamates elements from the top two experiments, suggesting a convergence of characteristics and trends in the Pareto approximate sets. This convergence may signify a synthesis of optimal policies that balance distributive justice considerations with overall system performance.

Figure 5.6: Parallel Coordinate Plots of the Pareto approximate set for the four experiments where each experiment is A Priori optimized for their respective problem formulation (a) Reference (b) Utilitarian (c) Prioritarian (d) Egalitarian. The objectives used for A Priori optimization are highlighted by a light-blue box. The remainder non-highlighted objectives are used for A Posteriori Evaluation. The colored lines show the single best solution for each objective. a) * Best Sudan 90^{th} overplotted by Best Sudan Irr. * Best Prioritarian overplotted by Best Sudan Irr. b) * Best Prioritarian overplotted by Best Sudan 90^{th}. c) * Best Utilitarian overplotted by Best Sudan Irr. * Best Prioritarian overplotted by Best Sudan 90^{th}.

The final Subfigure 5.6d displays a total of 338 solutions, a considerably larger number than in the previous experiments. This experiment further confirms that the Ethiopian Hydropower objective aligns with compromise solutions that strike a balance for all stakeholders, in lign with the commment in section 5.1. This alignment is evident as the shift towards higher Egalitarian solutions in the optimization process corresponds to a similar shift in the optimal policy for the Ethiopia Hydropower objective. Notably, there is an expanded solution space observed for both the Egypt Irrigation Deficit objectives and the Egalitarian objective. To better visualize the trajectory of the newly covered ranges, an additional plot focused on this aspect is presented in sub-figure 5.7.

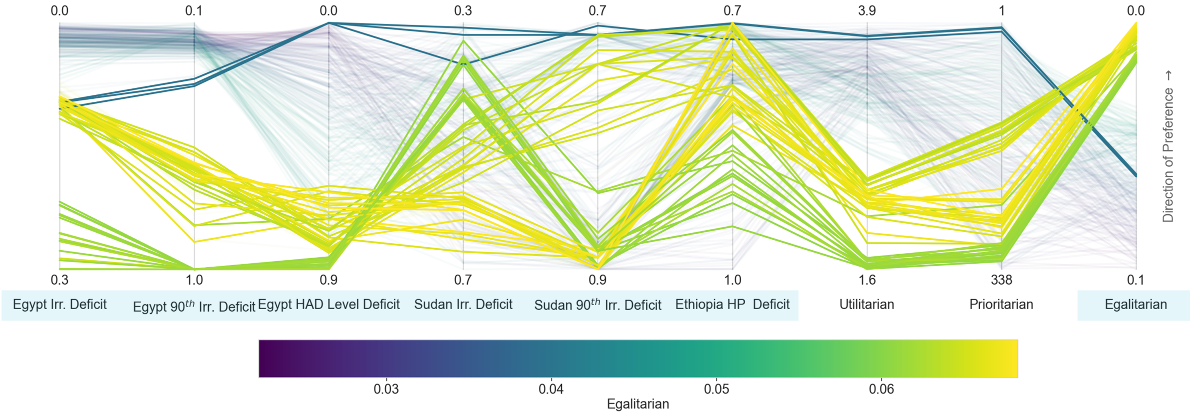


Figure 5.7: Parallel Coordinate Plot of Pareto approximate set for the Egalitarian Experiment with the solutions colored by their Egalitarian score as the continuous scale. Only solutions that score higher on the Egypt Irrigation Deficit than Reference, Utilitarian and Prioritarian are isolated, by brushing the rest. The objectives used for A Priori optimization are highlighted by a light-blue box. The remainder non-highlighted objectives are used for A Posteriori Evaluation.

Figure 5.7 displays three solution patterns. The key takeaway is from the blue solutions, indicating that high-scoring policies across objectives score poorly on the Egalitarian formulation, maintaining existing inequalities. Solutions achieving high scores either favor Ethiopian Hydro-power (yellow) or benefit Sudan's Irrigation deficit (green), showing a trade-off between these objectives in the top range of Egalitarian solutions.

To better understand the solutions that are created and if they resemble the general concepts of the problem formulations, an exploration of a broader spectrum of solutions beyond the single best is imperative. This exploration is depicted in Figure 5.8, accentuating the problem formulations that displayed notable deviations from the Reference Problem Formulation. For a comprehensive overview, the full plot is provided in Appendix B.2.

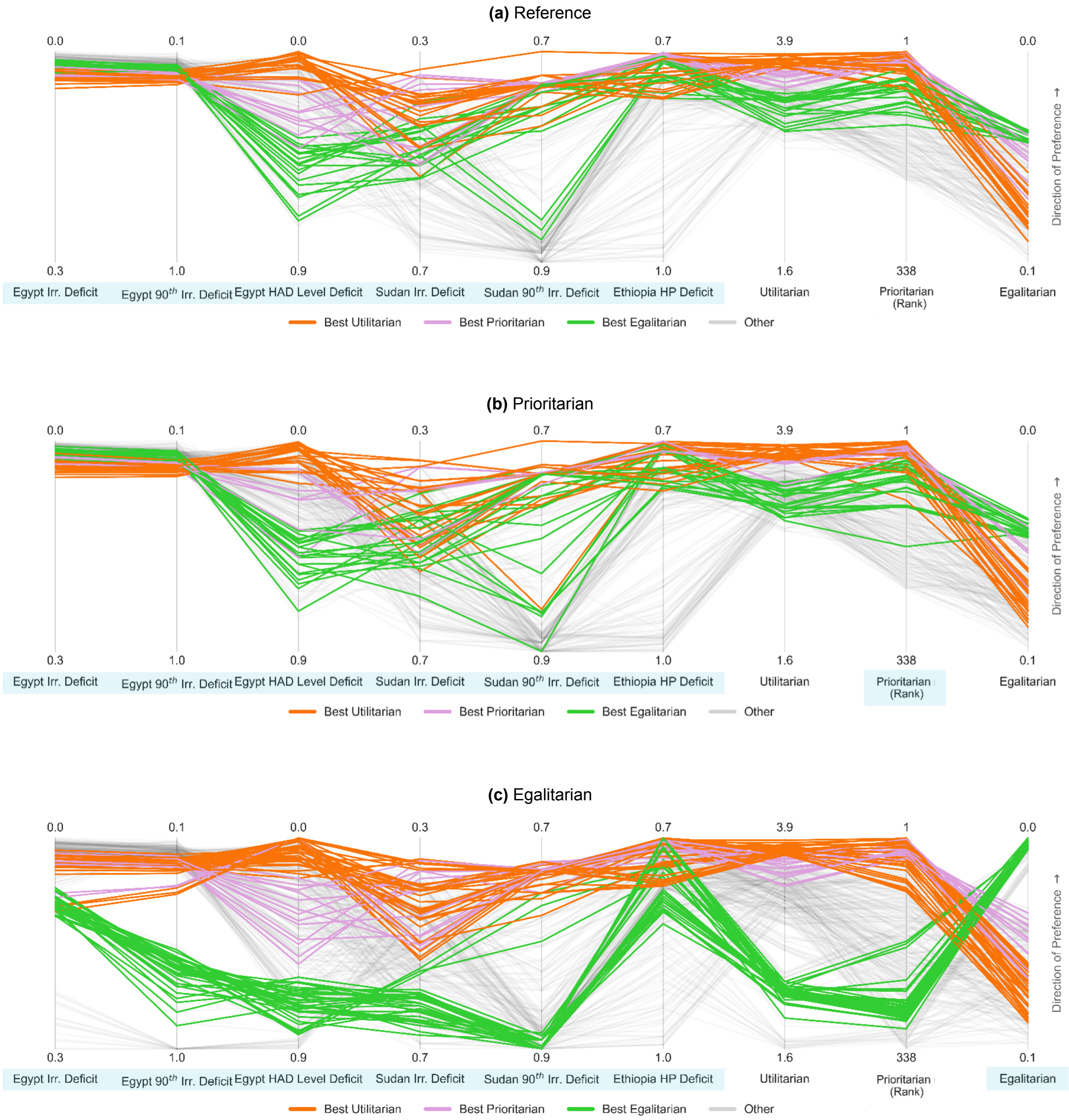


Figure 5.8: Parallel Coordinate Plots of the Pareto approximate set for three experiments where each experiment is A Priori optimized for their respective problem formulation (a) Reference (b) Prioritarian (c) Egalitarian. The objectives used for A Priori optimization are highlighted by a light-blue box. The remainder non-highlighted objectives are used for A Posteriori Evaluation. The colored lines show the 10^th percentile best solution for the Utilitarian, Prioritarian and Egalitarian Problem Formulations.

In Sub-figure 5.8b, it is evident that nearly all 10^{th} percentile Prioritarian solutions exhibit higher scores on the Utilitarian metric during A Posteriori evaluation. However, there is no noticeable emergence of significantly novel or improved solutions specific to the Prioritarian metric, a conclusion complicated by the stretched scale of this problem formulation. Subsequently, in Sub-figure 5.8c, a shift in trade-off patterns is observed, with a pronounced and robust trade-off between the Egalitarian metric and both the Utilitarian and Prioritarian metrics. The A Priori incorporation of the Egalitarian Problem Formulation reveals the favorability of new solutions that achieve considerably lower scores across nearly all objectives. A deeper understanding of the effect of an A Priori incorporation is gained in the following section by comparing the results with the A Posteriori approach.

5.4. Comparing The A Priori and A Posteriori Experiments

The preceding figures highlight the distinct solution sets resulting from various A Priori integrations. To further elucidate whether these integrations produce solutions that demonstrably perform better or worse, the scores for each Distributive Justice metric in different experiments are depicted in Figure 5.9.

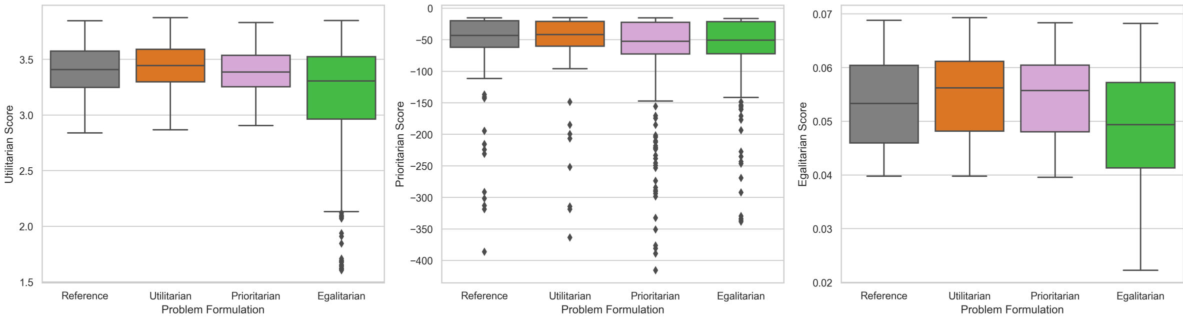


Figure 5.9: The Objective Value Ranges Reached for every experiment.

In terms of the Utilitarian metric, it is discernible that the average score slightly increases with the inclusion of a Utilitarian Problem Formulation. Additionally, the incorporation of an Egalitarian Problem Formulation results in a slightly lower average, accompanied by a considerably wider range of lower-scoring solutions. On the other hand, the integration of a Prioritarian Problem Formulation contributes to an expanded set of solutions exhibiting pronounced un-Prioritarian characteristics, evident from the stretched bottom range. Notably, the inclusion of the Egalitarian problem formulation consistently leads to an improvement in the average solution score. Since in contrast with the other metrics lower values are desirable. These conclusions are based on the aggregated values for all policies in the solutions set. Since for policy selection one can be interested in the best solutions for a certain objective instead of the full solution set, the ranges for the top $10^{th} percentile$ of every objective is shown below.

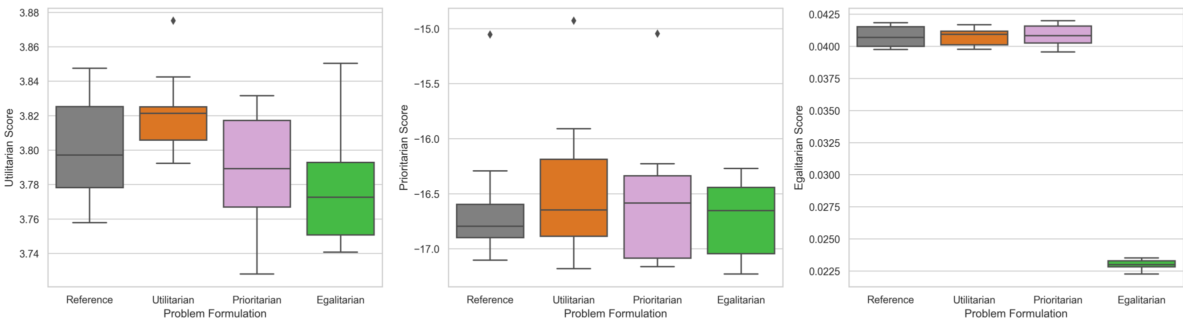
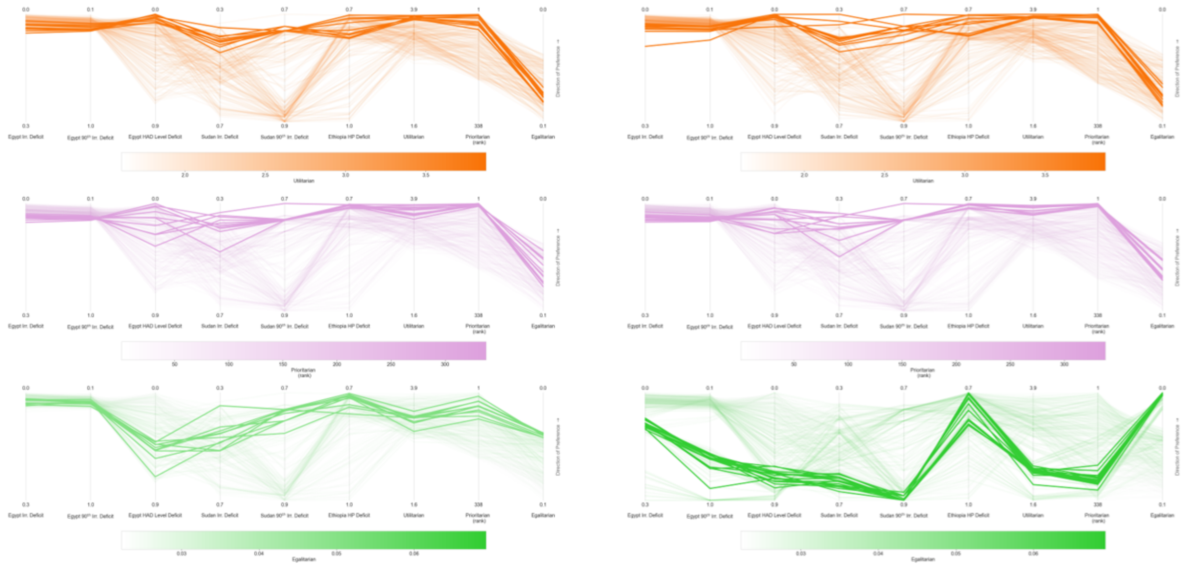


Figure 5.10: The Objective Value Ranges Reached for the top 10^{th} percentile solutions of every experiment.

If we compare figure 5.10 with the previous plot of figure 5.9, we see starker differences between the experiments. The A Priori integration of the Utilitarian problem formulation seems to outperform most solutions that remain after an A Posteriori filter of the other experiments. For the Prioritarian score we now do see an opposite effect of incorporating the problem formulation A Priori, the results score higher on the median level. It is striking that the Utilitarian experiment seems to perform better on the Prioritarian metric. For this an explanation is still to be found. In the final boxplot it is very clear that an A Priori incorporation of the Egalitarian problem formulation does generate a beneficial effect on the Egalitarian score. This corresponds with the extension of the bottom range in figure 5.9. The following figure shows whether we can understand this behavior by looking at the objectives that benefit or are penalized by every problem formulation.



(a) A Posteriori **(b)** A Priori

Figure 5.11: Parallel Coordinate Plots comparing the trade-offs changes for an A Posteriori approach, the filter of the solution set from the Reference experiment (a) versus the trade-offs found using an A Priori approach, optimizing for its own Distributive Justice problem formulation (b). The solutions are coloured based on the performance on every problem formulation that is compared on every yaxis level, top Utilitarian, middle Prioritarian, bottom Egalitarian. The solution sets are also brushed bringing the top 10^{th} percentile to the front.

The patterns in figure 5.11 provide the concluding comparison to understand whether an A Priori incorporation of the Distributive Justice principles is favorable compared to an A Posteriori evaluation. The A Priori Utilitarian incorporation is favorable for Sudan as new solutions are found for both of their objective values. The Prioritarian A Priori optimization mainly effects HAD level deficits reached across the upper and bottom range of that metric. The Egalitarian plots show strong trade-off changes based on whether an A Priori or A Posteriori approach is applies. The A Priori integration creates a much stronger trade-off with the objectives for both Egypt and Sudan favoring Ethiopia.

6
Discussion

This study constitutes a substantial contribution by exploring methods of integrating distributive justice principles into many-objective optimization. Within the scope of the Eastern Nile River Basin primary achievement lies in outlining the social and demographic conditions of the Eastern Nile River Basin and examining the implications of different Distributive Justice principles on the optimization process for reservoir management. Through A Priori incorporation of principles such as Utilitarianism, Egalitarianism, and Prioritarianism, the research showed new found policies for corporation in the river basin. It uncovers trade-offs and conflicts between the original objectives and fairness principles, offering a nuanced understanding of the decision-making landscape. Within the broader scientific scope of the research, methodological advances are made by showing the significant impact of different methods for evaluation on the Pareto approximate set. Additionally, first explorations are made on how to incorporate principles A Priori, which provides opportunity for creating best-practices.

While the study presents promising insights, it acknowledges certain methodological limitations. These are communicated by first highlighting the valuable insights found by conducting this study, presented in 6.1, and then contrasting these with the limitations in section 6.2.

6.1. Valuable Insights from the Study

The results provide a comprehensive exploration of the effects of incorporating Utilitarian, Egalitarian, and Prioritarian Problem Formulations in Many-Objective Optimization for the Eastern Nile River Basin case. The first phase that focused on doing this by applying an A Posteriori evaluation showed that this more conventional approach already provides a reordering of the ranking for the same solution set.

The A Priori integration results align with the anticipated behavior outlined in Chapter 2. While there is a discernible impact on the perceived solution ranges for each problem formulation, the mean scores exhibit a relatively modest effect. Notably, unexpected behavior was observed for the Prioritarian problem formulation, where A Priori incorporation appeared to decrease the Prioritarian average score in the solution set. Nevertheless, substantial changes in the identified solution space and corresponding trade-offs were evident for all problem formulations. This highlights the analytical strength of this approach as a tool for exploring potentially overlooked favorable solutions by introducing Distributive Justice problem formulations.

In establishing the distinctive effects of A Posteriori and A Priori incorporation, additional insights emerged. Specifically, an Egalitarian problem formulation proved conducive to identifying cooperative solutions, potentially leading to a lower total value of aggregate welfare. This observation aligns with the critique mentioned in Section 2.2.2, indicating that, on average, the current framework experiences ”Leveling down” for the Egalitarian principle. This behavior doesn’t appear for the Prioritarian principle, while this problem formulation also found solutions that have smaller relative distance between the objectives. It’s noteworthy that while Figure 5.7 illustrated a trade-off between Egalitarian and Utilitarian metrics, the relationship is not strictly composite. Through a thorough exploration of the solution space, opportunities exist to enhance both the Egalitarian score and the Utilitarian score. Lastly, it’s crucial to highlight that the measurement of Distributive Justice within the Social Welfare Framework isn’t solely contingent on the chosen problem formulation. Equally significant are the definitions of objectives, as they shape the measurement of inequality in the status quo. This on its turn influences the direction of the optimization algorithm when a Prioritarian or Egalitarian problem formulation is incorporated.

6.2. Limitations of the Study

For this study, the frameworks delineated in Chapter 3, encompassing the Social Welfare Framework and the case-study model, were meticulously selected and applied. However, it is imperative to recognize that every theory, framework, and model is inherently imperfect. Consequently, this section critically explores the limitations inherent in these key research decisions.

6.2.1. Limitations in the Social Welfare Framework

Prioritarian SWFs

The implementation of Atkinson social welfare functions (SWFs) provides valuable insights, yet it is crucial to acknowledge their limitations. Atkinson SWFs necessitate non-negative well-being values, posing challenges when confronted with diverse well-being levels. Sensitivity near zero thresholds raises concerns, emphasizing the need for circumspection in their application. While instrumental in certain contexts, these assumptions of okay behaviour become limitations that warrant careful consideration if this is not understood (Adler and Treich, 2015).

Atkinson SWFs Domain Constraints: Atkinson SWFs necessitate that the input well-being values be non-negative. In cases where $\gamma \geq 1$, these values must be strictly positive. This stipulation can be attributed to the properties of the Atkinson $g(\cdot)$ transformation function, which is either undefined or lacks the requisite properties of being both monotonically increasing and strictly concave when confronted with negative well-being values. Moreover, for $\gamma \geq 1$, the function encounters complications with an input of zero.

Atkinson SWFs Behavioral Anomalies at Zero Point: Even for modest values of γ, Atkinson SWFs demonstrate pronounced sensitivity as well-being levels verge on the zero threshold. Specifically, as a given individual’s well-being level approximates zero, the proportional emphasis or weight accorded to marginal increases in her well-being, juxtaposed against fluctuations in the well-being of a relatively better-off individual, tends to be unbounded.

Aggregation rule

Additionally, the aggregation of welfare within a single group, as discussed by Adler (Adler and Treich, 2015), prompts reflection on its implications. The potential exclusion of disadvantaged subgroups within the broader population underscores the importance of refining our understanding of justice metrics.

Equality of Opportunity Theory

Currently, there has been no incorporation of the Equality of Opportunity Theory, which improves utilitarian social welfare theory based on critique number two discussed in 2.2.1. This could be implemented by incorporating a social welfare function of the following class.

$$S^V = \sum_{i=1}^{n} \sum_{j=1}^{m} p_j^i g^i(w_j^i) \tag{6.1}$$

6.2.2. Limitations of the Simulation Model

Incommensurability of Objectives

The challenge posed by 'incommensurability,' as defined by Craswell (1998), refers to the lack of a common measure or standard for comparing the values of two different concepts or entities. It manifests in the Eastern Nile River Basin model due to the inherent difficulty in ranking options on the same scale. This challenge is particularly critical given the complexity of the objectives, each representing diverse aspects of water resource management. The model's objectives include:

- *Egypt Average Yearly Irrigation Demand Deficit*
- *Egypt 90th Percentile Worst Demand Deficit*
- *Egypt HAD Level Deficit*
- *Sudan Average Yearly Irrigation Demand Deficit*
- *Sudan 90th Percentile Worst Demand Deficit*
- *Egypt Hydropower Demand Deficit*

Reconciliation through Utility Functions Addressing incommensurability entails the use of utility functions to reconcile non-transferable goods. While this approach establishes a common scale for comparison, it falls short in providing a justification for prioritizing one value over another. The utility function, acting as a metric in Craswell's definition of incommensurability, becomes indispensable when evaluating Distributive Justice problem formulations, particularly in their aggregated form. However, it's imperative to acknowledge the limitations of utility functions in offering a substantive justification, especially in cases involving irreversible losses.

For instance, consider the Egypt Average Yearly Irrigation Demand Deficit and the Ethiopia Hydropower Demand Deficit. These two objectives, representing crucial aspects of water use, may lack a clear metric for direct comparison. The irrigation deficit, aimed at ensuring agricultural needs are met, and the hydropower deficit, addressing energy demands, could be deemed incommensurable due to the absence of a straightforward scale to measure their relative importance. Is a 10% deficit for agriculture equally bad as having a 10% energy deficit in your country? This inherent incommensurability poses a challenge in justifying the prioritization of one objective over the other based solely on utility functions. This challenge becomes even more pronounced in the context of Distributive Justice problem formulations, as it may lead to the creation of misleading notions of equality.

Flooding

The simulation model used in this study has its own set of limitations, impacting the robustness of our results. Notably, the absence of flooding considerations in the simulation, despite anticipated increases in precipitation shown in figure 3.4, highlights a critical gap. Future iterations of the model should incorporate flood-risk assessments to provide a more comprehensive understanding of the system dynamics.

District aggregation

Similarly, the aggregation of different irrigation districts for Sudan in the simulation model deserves attention. This simplification may obscure nuanced variations within the country, limiting the precision of the distributive justice analyses. Future models should strive for a more granular representation to capture localized impacts accurately.

7
Conclusion

The research is concluded by summarizing the findings while also explaining the limitations that need to be considered and possibly further researched. The latter is vital to understand, for the findings to be extended or implemented.

7.1. Summary of Findings

The following answers to the subquestions can be concluded from this research in order to answer the main research question:

How to incorporate Distributive Justice Principles within Many-Objective Optimization Modeling?

What are different perspectives on commonly used Principles of Distributive Justice?

In addressing the various perspectives on commonly used Principles of Distributive Justice, this study has navigated through the ethical frameworks of Utilitarianism, Egalitarianism, and Prioritarianism. Each principle has its unique approach to the distribution of societal goods and benefits. The utilitarian emphasis on maximizing overall happiness, egalitarian pursuit of equality, and prioritarian focus on the least advantaged provide decision-makers with distinct ethical lenses. Critiques associated with each principle underscore the challenges of translating abstract ethical concepts into practical policy frameworks.

How and at which step of the modeling process can Distributive Justice principles be translated into a Many-Objective Optimization model?

Incorporating Distributive Justice principles as objective functions with the Social Welfare Framework provides the opportunity to quantify fairness without relying on static constraints. This does pose challenges in defining proper problem formulations due to the high chance of in-commensurable data with the high amount of objectives in MOO. In order to compare the ENRB objectives all objectives need to quantified as deficit ratios. This creates six country objectives, Egypt Irr. Deficit, Egypt 90^{th} Irr. Deficit, Egypt HAD Level Deficit, Sudan Irr. Deficit, Sudan 90^{th} Irr. Deficit, and the Ethiopia HP Deficit, for the Reference problem formulation. An Utilitarian problem formulation can be formed by aggregating the six Reference objectives. A Prioritarian problem formulation can be applied that prioritizes subordinate objectives using a transformation function. An Egalitarian problem formulation calculates relative distances to measure the equality between the objectives.

What trade-offs are observed when evaluating the Many-Objective Optimization model using different Distributive Justice principles A Posteriori?

The A Posteriori experiments presented in Section 5.2 provide valuable insights by filtering the optimization outcomes of the Reference Experiment using the reference problem formulation. By incorporating Utilitarian, Prioritarian, and Egalitarian fairness metrics, we extend our understanding beyond the initial country objectives. The parallel coordinates plot in Figure 5.2 visually captures the trade-offs and highlights solutions favored by these additional metrics. Notably, the 10^{th} percentile analysis in Figure 5.3 delves deeper, showcasing distinctive patterns and preferences within this subset of optimal solutions. The A Posteriori Evaluation unveils unique solution behaviors, emphasizing the necessity of considering diverse fairness perspectives in water resource management optimization. This exploration enhances our ability to identify policies that may be overlooked by non aggregated objectives. This fairly simple post-processing step already contributes to more informed decision-making.

How does the a priori integration of the Distributive Justice principles in the Many-Objective Optimization model compare to evaluating them a posteriori?

In conclusion, the a priori integration of Distributive Justice principles in the MOO model presents a distinct approach compared to evaluating them a posteriori. The decision to incorporate ethical principles a priori influences the shape, the ranges and the trade-offs of the solution sets. The comparison between A Priori and A Posteriori experiments, as illustrated in Figures 5.9 and 5.10, showed that the Utilitarian and Egalitarian metrics benefit from an A Priori integration. An A Priori Prioritarian optimization is only beneficial if the interest lays in finding the best performing solutions. Otherwise an A Posteriori evaluation creates a similar effect. Parallel Coordinate Plots in Figure 5.11 showed a similar effect. The plots highlight the trade-offs shifts between A Posteriori and A Priori approaches for all three problem formulations.

Furthermore, integrating ethical principles a priori initiates a discussion about fairness before the analysis, fostering transparency and preventing potential biases introduced by post hoc evaluations. By selecting an ethical principle in advance, the decision-maker avoids being influenced by the results, maintaining a clearer ethical stance throughout the optimization process. This approach also provides a more transparent and accountable decision-making process, as stakeholders are aware of the chosen ethical framework from the outset.

It is essential to acknowledge the trade-offs involved in incorporating problem formulations a priori. While it does increase computation time due to the added complexity in the model, the potential for more relevant and ethically aligned results justifies this investment. This trade-off underscores the importance of carefully considering the specific case characteristics, the ethical principles at play, and the goals of the decision-making process.

In summary, the A Priori integration of Distributive Justice principles in MOO not only aid to the relevance of the results but also promotes a proactive and transparent approach to ethical decision-making in complex scenarios.

7.2. Scientific Relevance

The scientific relevance of this study lies in its contribution to the evolving field of multi-objective optimization (MOO) with a focus on distributive justice principles. By incorporating Utilitarian, Egalitarian, and Prioritarian Problem Formulations, the research expands the conventional MOO framework, providing a more nuanced understanding of decision-making processes. The study delves into the complexities of applying ethical views within MOO, shedding light on how different principles impact the Pareto approximate set and trade-off landscapes. This exploration contributes to the broader discourse on ethical considerations in optimization and decision science

7.3. Societal Relevance

The study highlights the importance of considering distributive justice principles in decision-making for the Eastern Nile River Basin. Trade-offs and conflicts between fairness principles and original objectives necessitate careful consideration since it affects marginalized communities. The methodology provides a nuanced understanding of how incorporating different problem formulations impacts the decision-making process. With these insights a start is made towards a research narrative in which the decision-maker can decide which ethical view and matching Distributive Jutice principles are deemed fitting for the case and can easily implement them both A Priori and A Posteriori instead of being limited towards the conventional Utilitarian Distributive Justice Principle.

7.4. Future Directions

7.4.1. Other principles of Distributive Justice

Due to time-constraints within this research, only two new ethical views were implemented for the ENRB case. These principles were chosen based on the fact that they were more general less niche principles, while still being very distinct. A focus on other less common principles of Distributive Justice would provide novel insights. Incorporating the Equality of Opportunities theory is just one example.

7.4.2. Covariance for Results Interpretation

One considered but not explored angle is the use of covariance as a metric for interpreting results. This could show relations between the Objectives that are not easily visible by the ranges or trade-off structure.

7.4.3. Framework for Decision-making process

As can be seen from the elaborate Parallel Coordinates Plots in chapter 5, the ability of comparing different principles at different modelling steps increases the amount of information to digest as a decision-maker. This also makes the analysis more complex, adding complexity in communicating this information with stakeholders or other parties. Something which currently is already seen as a challenge in Many-Objective Optimizationl due to the high-dimensionality. Now that is shown that incorporating Distirbutive Justice principles A Priori has an effect on the Pareto approximate set, it is needed have a clear framework on how to use this extra information. This requests more research on *1)* how to decide which principles to incorporate based on the case-characteristics?, *2) how to use the added information for effectively finding stable solutions? 3) how to communicate the findings effectively with stakeholders?*

8 Reflection

Insights from Conducting this Thesis Research

Embarking on this thesis journey has revealed a realization: despite the abundance of insightful ideas, the limitation of time hinders the exhaustive development of each notion. This became a recurring theme as I progressed, leading me to let go of certain ideas, such as incorporating adaptive gammas for the Prioritarian Problem Formulation, though the persistent urge to develop them lingers, fueled by curiosity and a strong belief in their potential usefulness for the research. Another insight echoes the wisdom imparted by professors throughout my study, from Dr. P.W.G. Bots in my first modeling course in the Bachelor to Prof.dr.ir. A. Verbraeck in my master specialization course, emphasizing the importance of applying Occam's razor in model selection, an approach advocating for simpler solutions when all else is equal (Blumer et al., 1987). While the case model used for this research pushes the state-of-the-art in reservoir modeling, it complicates testing the problem formulations, prompting a critical examination of the usefulness of the additional layers of detail for the main focus of this research.

Learning Novel Concepts

The joy derived from conducting this research stems from the myriad of new concepts learned throughout the process. Firstoff, the all the concepts of Philosphy, that started with an exploration of Distributive Justice principles but meant a study going to distinctions between Descriptive and Normative Ethics or Deontology and Consequentialism. But also on the technical side I have learned new concepts such as, comprehending the intricacies of High-Performance Computing, exploring optimization algorithms like epsilonNSGAII and Borg, creating clean code file structures, Profiling for runtime optimization and navigating the effective use of Git have enriched my learning experience. While I was familiar with Git as a platform for code sharing, incorporating it seamlessly into my research workflow marked a novel and valuable skill.

Learning to Master Skills

This research journey has served as a platform for professional growth in the skills that I already had and also stretch outside this domain. Object-oriented modeling, data visualization, and improved debugging skills now stand as refined aspects of my skill set. The course Model-Based Decisionmaking thought me the concepts of the EMA Workbench, but in hindisight I knew very little about its inner workings. The moment I dived inside the package source-code, I realized I now realy was starting to understand the innerworkings. The thesis pushing me to dive into these details made me a better programmer.

Key Take-Aways Looking Back and Going Forward

The culmination of this thesis project has brought forth a resounding confirmation — I genuinely enjoy the research process. Moreover, it has kindled a newfound interest in Philosophy and Economics. Notably, I find myself identifying the concepts from literature in the news and books I engage with, establishing a meaningful connection between theoretical knowledge and real-world occurrences. I find it very valuable that in this way the thesis in the final stage of my master really has a lasting impact on me as a policy-analyst.

References

Abdalla, I. H. (1971). The 1959 nile waters agreement in sudanese-egyptian relations. *Middle Eastern Studies*, 7(3):329–341.

Abu-Zeid, M. A. and Biswas, A. K. (1991). Some major implications of climatic fluctuations on water management. *International Journal of Water Resources Development*, 7(2):74–81.

Ackoff, R. (1978). *The Art of Problem Solving: Accompanied by Ackoff's Fables*. A Wiley-interscience publication. Wiley.

Adler, M. D. (2019). *Measuring social welfare: An introduction*. Oxford University Press, USA.

Adler, M. D. and Norheim, O. F. (2022). *Prioritarianism in practice*. Cambridge University Press.

Adler, M. D. and Treich, N. (2015). Prioritarianism and climate change. *Environmental and Resource Economics*, 62:279–308.

Arneson, R. J. (1989). Equality and equal opportunity for welfare. *Philosophical Studies: An International Journal for Philosophy in the Analytic Tradition*, 56(1):77–93.

Arsano, Y. and Tamrat, I. (2005). Ethiopia and the eastern nile basin. *Aquatic Sciences*, 67(1):15–27.

Atkinson, A. B. (1970). On the measurement of inequality. *Journal of Economic Theory*, 2(3):244–263.

Bentham, J. (1789). *An Introduction to the Principles of Morals and Legislation: Printed in the Year 1780, and Now First Published*. Goldsmiths'-Kress library of economic literature 1450-1850. T. Payne.

Bergson, A. (1938). A reformulation of certain aspects of welfare economics. *The Quarterly Journal of Economics*, 52(2):310–334.

Blumer, A., Ehrenfeucht, A., Haussler, D., and Warmuth, M. K. (1987). Occam's razor. *Information Processing Letters*, 24(6):377–380.

Chand, S. and Wagner, M. (2015). Evolutionary many-objective optimization: A quick-start guide. *Surveys in Operations Research and Management Science*, 20(2):35–42.

Ciullo, A., Kwakkel, J. H., De Bruijn, K. M., Doorn, N., and Klijn, F. (2020). Efficient or fair? operationalizing ethical principles in flood risk management: A case study on the dutch-german rhine. *Risk Analysis*, 40(9):1844–1862.

Crabitès, P. (1929). The nile waters agreement. *Foreign Affairs*, 8(1):145–149.

Craswell, R. (1998). Incommensurability, welfare economics, and the law. *University of Pennsylvania Law Review*, 146(5):1419–1464.

Deb, K. and Jain, H. (2013). An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, part i: solving problems with box constraints. *IEEE transactions on evolutionary computation*, 18(4):577–601.

Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: Nsga-ii. *IEEE transactions on evolutionary computation*, 6(2):182–197.

Doorn, N. (2013). Water and justice: Towards an ethics of water governance. *Public Reason*, 5(1).

Driver, J. (2011). *Consequentialism*. Routledge.

Dworkin, R. (1981). What is equality? part 1: Equality of welfare. *Philosophy & Public Affairs*, 10(3):185–246.

Freeman, S. (2018). Rawls on distributive justice and the difference principle. In *The Oxford Handbook of distributive justice*, pages 1–33. Oxford University Press Oxford.

Gini, C. (1921). Measurement of inequality of incomes. *The Economic Journal*, 31(121):124–126.

Giuliani, M., Castelletti, A., Pianosi, F., Mason, E., and Reed, P. M. (2016). Curses, tradeoffs, and scalable management: Advancing evolutionary multiobjective direct policy search to improve water reservoir operations. *Journal of Water Resources Planning and Management*, 142(2):04015050.

Giuliani, M., Lamontagne, J., Reed, P., and Castelletti, A. (2021). A state-of-the-art review of optimal reservoir control for managing conflicting demands in a changing world. *Water Resources Research*, 57(12):e2021WR029927.

Gleick, P. H. and Heberger, M. (2014). Water and conflict. *The world's water*, pages 159–171.

Goor, Q., Halleux, C., Mohamed, Y., and Tilmant, A. (2010). Optimal operation of a multipurpose multireservoir system in the eastern nile river basin. *Hydrology and Earth System Sciences*, 14(10):1895–1908.

Groenfeldt, D. and Schmidt, J. J. (2013). Ethics and water governance. *Ecology and Society*, 18(1).

Hamad, O. E.-T. and El-Battahani, A. (2005). Sudan and the nile basin. *Aquatic Sciences*, 67:28–41.

Hasan, E., Tarhule, A., Kirstetter, P.-E., Clark, R., and Hong, Y. (2018). Runoff sensitivity to climate change in the nile river basin. *Journal of Hydrology*, 561:312–321.

Hefny, M. and Amer, S. E.-D. (2005). Egypt and the nile basin. *Aquatic Sciences*, 67:42–50.

Inselberg, A. and Dimsdale, B. (1991). *Parallel Coordinates*, pages 199–233. Springer US, Boston, MA.

Jansen, T., Wegener, I., and Kaufmann, P. (2001). On the utility of populations in evolutionary algorithms. In *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO)*, pages 1034–1041. Citeseer.

Jeffrey, P. (2018). Distributive justice, stability, and sustainable water resources management.

Kollat, J. B. and Reed, P. M. (2005). The value of online adaptive search: A performance comparison of nsgaii, ϵ-nsgaii and ϵmoea. In Coello Coello, C. A., Hernández Aguirre, A., and Zitzler, E., editors, *Evolutionary Multi-Criterion Optimization*, pages 386–398, Berlin, Heidelberg. Springer Berlin Heidelberg.

Kolm, S.-C. (1977). Multidimensional egalitarianisms. *The Quarterly Journal of Economics*, 91(1):1–13.

Lamont, J. (2017). *Distributive justice*. Routledge.

Lippert-Rasmussen, K. (2018). *Pluralist Egalitarianism*, page 181–210. Cambridge University Press.

Mason, S. J. A. (2004). *From Conflict to Cooperation in the Nile Basin: Interaction Between Water Availability, Water Management in Egypt and Sudan, and International Relations in the Eastern Nile Basin*. ETH Zurich.

Mill, J. (1863). *Utilitarianism*. The works of John Stuart Mill. Parker, Son and Bourn.

Moulin, H. (1985). The separability axiom and equal-sharing methods. *Journal of Economic Theory*, 36(1):120–148.

NBI (2023). Nile basin.

Negm, A., Elsahabi, M., Abdel-Nasser, M., Mahmoud, K., and Ali, K. (2018). Grand ethiopian renaissance dam versus aswan high dam.

Nozick, R. (1974). *Anarchy, State, and Utopia*. Harper Torchbooks. Basic Books.

Page, E. (2007). *Climate Change, Justice and Future Generations*. Edward Elgar Publishing, Incorporated.

Pareto, V. (1906). *Manuale di Economia Politica*. Societa Editrice Milano.

Parfit, D. (1995). *Equality or priority?* University of Kansas Kansas.

Rawls, J. (1971). *A Theory of Justice: Original Edition*. Harvard University Press.

Rittel, H. W. and Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy sciences*, 4(2):155–169.

Roemer, J. E. (1985). Equality of talent. *Economics & Philosophy*, 1(2):151–188.

Said, R. (2012). *The geological evolution of the River Nile*. Springer Science & Business Media.

Salman, S. M. (2013). The nile basin cooperative framework agreement: A peacefully unfolding african spring? *Water International*, 38(1):17–29.

Samuelson, P. (1947). *Foundations of economic analysis*. Harvard Economic Studies. Oxford University Press.

Sari, Y. (2022). Exploring Trade-offs in Reservoir Operations through Many Objective Optimisation: Case of Nile River Basin. Master's thesis, Delft University of Technology, the Netherlands.

Sarva, S. (2021). Operationalising stability and fairness in transboundary water resource allocations. Master's thesis, Delft University of Technology, the Netherlands.

Sen, A. (1979). Utilitarianism and welfarism. *The Journal of Philosophy*, 76(9):463–489.

Sen, A. (1980). *Equality of What?* Cambridge University Press, Cambridge.

Sen, A. (1999). *Development as Freedom*. Alfred Knopf, New York.

Sen, A. (2018). *Collective choice and social welfare*. Harvard University Press.

Stefik, M. and Bobrow, D. G. (1985). Object-oriented programming: Themes and variations. *AI magazine*, 6(4):40–40.

SWAIN, A. (1997). Ethiopia, the sudan, and egypt: The nile river dispute. *The Journal of Modern African Studies*, 35(4):675–694.

Swain, A. (2002). The nile river basin initiative: Too many cooks, too little broth. *SAIS Review*, 22:293–308.

Swain, A. (2011). Challenges for water sharing in the nile basin: changing geo-politics and changing climate. *Hydrological Sciences Journal*, 56(4):687–702.

Talbot, M. R. and Williams, M. A. (2009). Cenozoic evolution of the nile basin. *The Nile: Origin, environments, limnology and human use*, pages 37–60.

Taye, M. T., Willems, P., and Block, P. (2015). Implications of climate change on hydrological extremes in the blue nile basin: a review. *Journal of Hydrology: Regional Studies*, 4:280–293.

Tian, J., Guo, S., Liu, D., Pan, Z., and Hong, X. (2019). A fair approach for multi-objective water resources allocation. *Water Resources Management*, 33(10):3633–3653.

United Nations, Department of Economic and Social Affairs - Sustainable Development (2022). Transforming our world: the 2030 agenda for sustainable development.

Wheeler, K. G., Basheer, M., Mekonnen, Z. T., Eltoum, S. O., Mersha, A., Abdo, G. M., Zagona, E. A., Hall, J. W., and Dadson, S. J. (2016). Cooperative filling approaches for the grand ethiopian renaissance dam. *Water International*, 41(4):611–634.

Wheeler, K. G., Jeuland, M., Hall, J. W., Zagona, E., and Whittington, D. (2020). Understanding and managing new risks on the nile with the grand ethiopian renaissance dam. *Nature Communications*, 11(1):5222.

Yalew, S. G., Kwakkel, J., and Doorn, N. (2021). Distributive justice and sustainability goals in transboundary rivers: Case of the nile basin. *Frontiers in Environmental Science*, 8.

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., and Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Sciences*, 77:161–170.

Zatarain Salazar, J., Reed, P. M., Herman, J. D., Giuliani, M., and Castelletti, A. (2016). A diagnostic assessment of evolutionary algorithms for multi-objective surface water reservoir control. *Advances in water resources*, 92:172–185.

A

Appendices - Methodology

A.1. Actor Perspectives

This section explores the dynamics within the Eastern Nile River Basin, focusing on the diverse perspectives and strategies adopted by key riparian countries. Ethiopia, Egypt, and Sudan emerge as central actors, each contributing a unique historical, economic, and developmental context to the ongoing discourse around the GERD.

A.1.1. Ethiopia and Water for Development

Ethiopia has over 80% of its population residing in rural areas and more than 70% employed in agriculture. The country faces challenges in electricity access, with only 27% of the population connected to the grid. The Ethiopian government, recognizing water resources management as a bottleneck for economic prosperity, has demonstrated ambition in this regard. However, Ethiopia's steps challenge the status quo and hydro-hegemony in the basin. Despite having the upper hand as an upstream riparian country with a growing population and GDP, Ethiopia faces inertia due to historical power relations in the basin. The construction of micro-dams and the initiation of GERD's construction marked significant shifts in Ethiopia's water development strategies, aiming at catalyzing economic growth through improved electricity access.

A.1.2. Egypt's Water Security and Economic Considerations

Egypt stands out among riparian countries with over 99% of its population connected to electricity and clean water networks. With the highest GDP per capita, Egypt has historically benefited from Nile water for its agricultural economy. The construction of the High Aswan Dam enhanced Egypt's control over the Nile flow, addressing seasonal demand but causing significant water loss due to evaporation. Diversification of the economy and import of water-intensive products are key strategies for Egypt's water security. Egypt opposes the GERD, citing concerns about decreased downstream water flow, which would impact food and energy security.

A.1.3. Sudan's Agricultural Economy and Shifting Stance on GERD

Sudan's economy, characterized by a strong agricultural focus, relies on approximately 50% of its population engaged in agriculture. The country has room for improvement in electricity access, with 35% of the population currently connected. Sudan's modern agriculture traces back to the colonial era, and decisions related to the Nile, a crucial water source, are of significant importance. Unlike Egypt, Sudan's initial concerns about the GERD softened over time. The regulation of the highly variable Blue Nile water flow, seen as beneficial for managing flooding issues, contributed to this shift in Sudan's stance.

A.2. Broad Description of ε-NSGAII

The ε-NSGAII is a genetic algorithm that utilizes genetic operators (selection, crossover, and mutation) in its search process (Jansen et al., 2001). The algorithm initiates with a population, then iteratively selects solutions to form a mating pool. In the context of genetic algorithms and evolutionary algorithms like ε-NSGAII, the term ”population” refers to a set of potential solutions to the optimization problem (Chand and Wagner, 2015).

Each individual solution in the population is represented by a set of parameters (or variables) that can be modified by the algorithm. The quality of each solution is evaluated using a fitness function (or objective function) that measures how well the solution satisfies the optimization objectives.

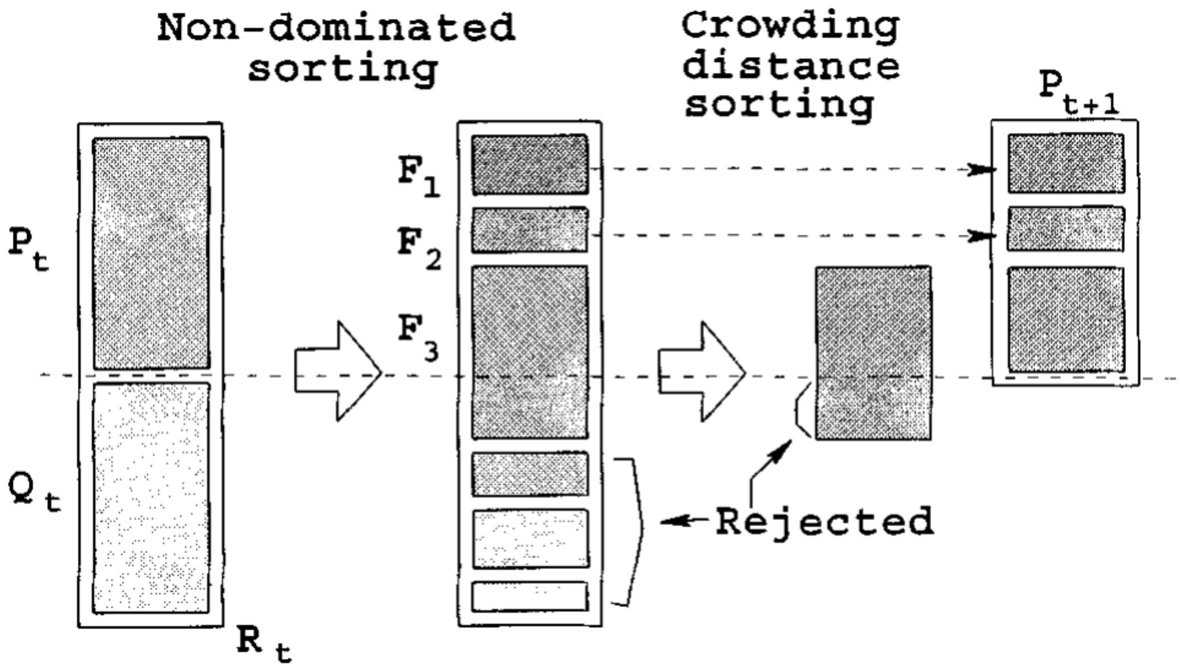
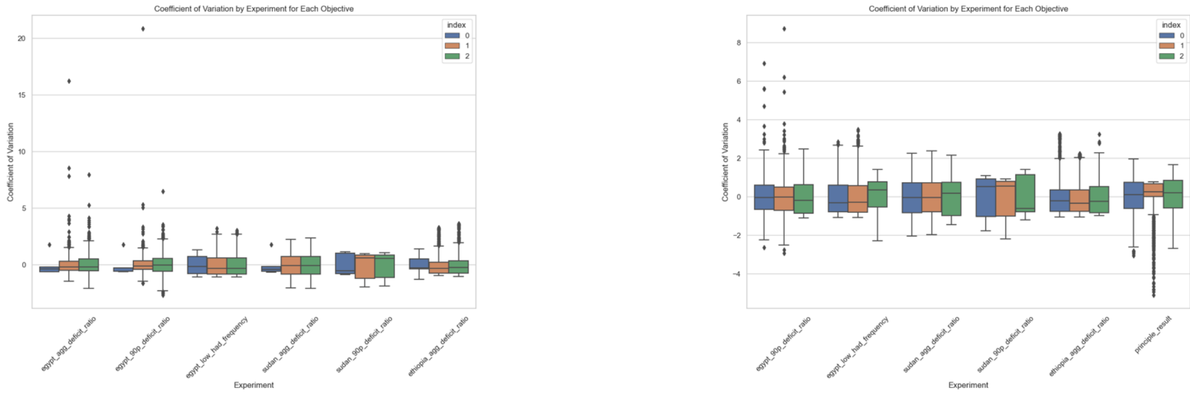


Figure A.1: NSGA-II procedure from Deb et al. (2002), with population P, off-spring population Q, combined population R, and non-dominated sets F_N.

During the optimization process, the algorithm uses genetic operators to create new solutions (offspring) from the current population. This procedure is illustrated in A.1. The new offspring and the current population are then combined, and the best solutions are selected to form the next generation’s population. This process is repeated until a stopping criterion is met, such as a maximum number of function evaluations. Offspring are generated via crossover and mutation from this pool. Thus crossover and mutation rates are parameters in genetic algorithms (GAs) and evolutionary algorithms (EAs) that affect the algorithm’s performance and the quality of the final solution. Crossover rate is the probability that two parent solutions will exchange some portions of their structure (i.e., genes) to create new child solutions. Mutation rate is the probability that a small random change will be applied to a newly created child solution. The offspring and current population are then amalgamated, and non-dominated sorting is employed to select the best solutions for the subsequent generation.

A critical component of the ε-NSGAII algorithm is the concept of ε-dominance. Traditionally, in Pareto dominance, a solution is deemed better than another if it is equal or superior in all objectives and strictly superior in at least one objective (Pareto, 1906). However, in ε-dominance, a solution is considered superior to another if it is equal or superior in all objectives and better by at least a factor of ε in at least one objective. This concept aids in reducing the Pareto front size, rendering the algorithm more computationally efficient (Deb and Jain, 2013).

A.3. Setting configurations



(a) Simulation **(b)** Evaluation

Figure A.2: The epsilon and NFE experiments.

B

Appendices - Results

B.1. Ranked Prioritarian scale in Parallel Coordinate Plot of Reference Experiment.

In this section, we present the altered version of the Prioritarian axis in contrast to Figure 5.2.

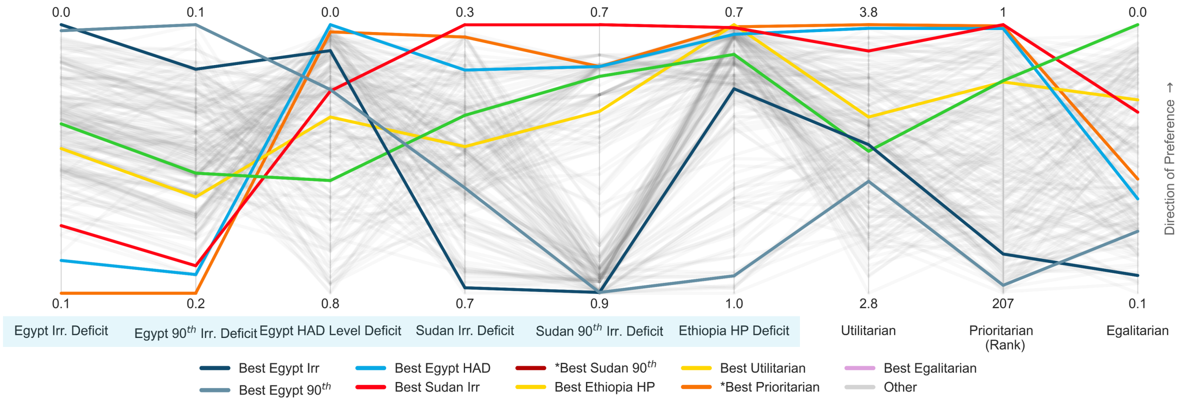


Figure B.1: Parallel Coordinate Plots of the Pareto approximate set with A Posteriori evaluation of the Reference Experiment. The objectives used for A Priori optimization are highlighted by a light-blue box. The remainder non-highlighted objectives are used for A Posteriori Evaluation. The colored lines show the single best solution for each objective. * Best Sudan 90^{th} overplotted by Best Sudan Irr. * Best Prioritarian overplotted by Best Sudan Irr.

B.2. Full Paralell coordinates

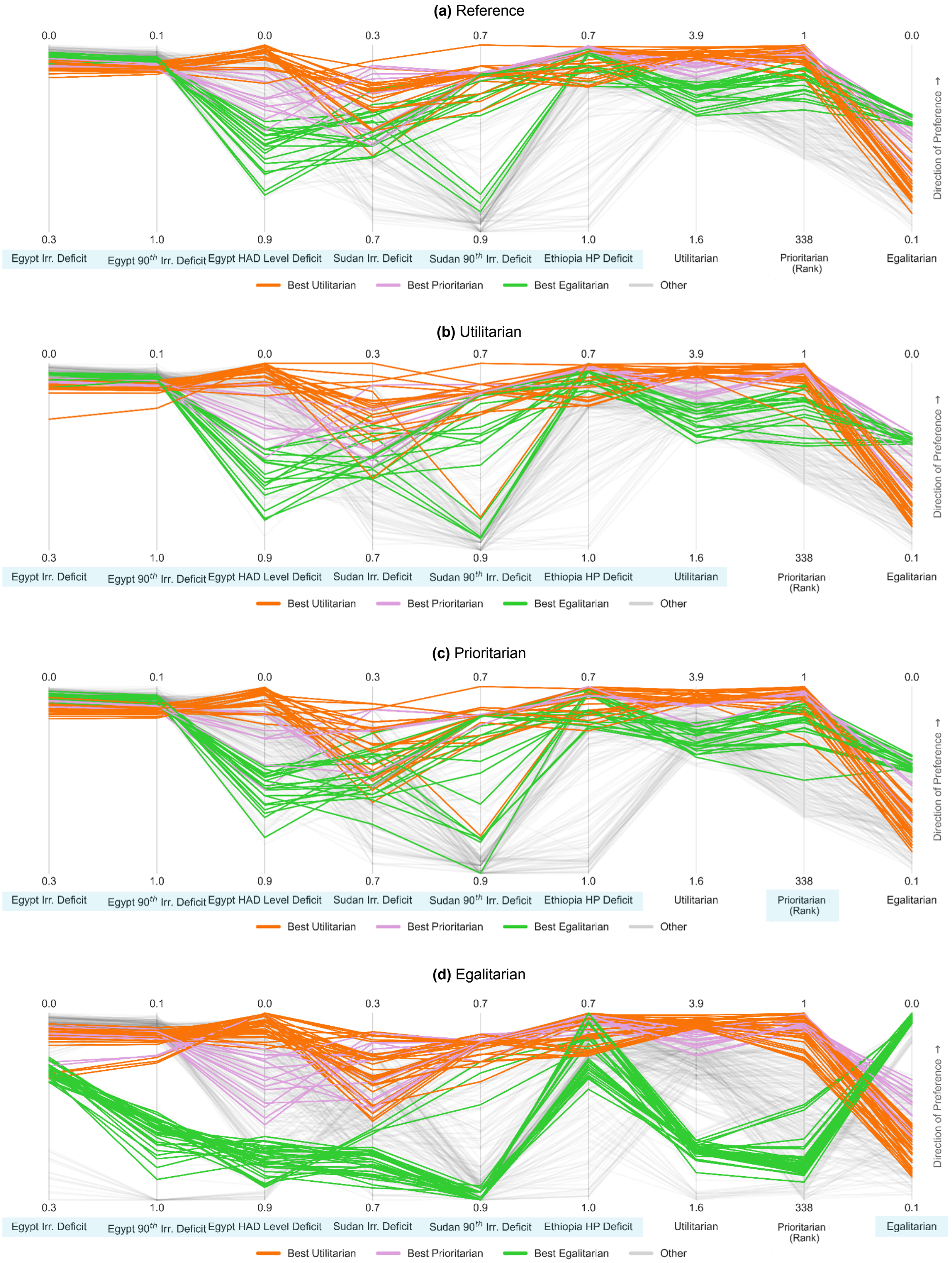


Figure B.2: Full: Parallel Coordinate Plots of the Pareto approximate set for four experiments where each experiment is A Priori optimized for their respective problem formulation (a) Reference (b) Utilitarian (c) Prioritarian (d) Egalitarian. The objectives used for A Priori optimization are highlighted by a light-blue box. The remainder non-highlighted objectives are used for A Posteriori Evaluation. The colored lines show the 10^th percentile best solution for the Utilitarian, Prioritarian and Egalitarian Problem Formulations.

B.3. Model Verification

B.3.1. Convergence

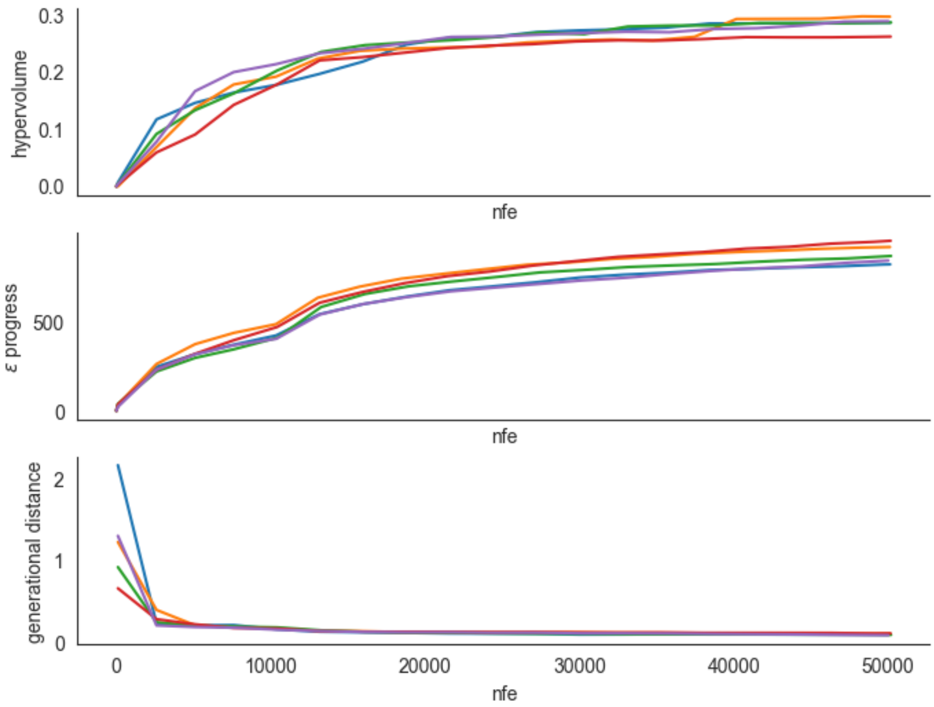


Figure B.3: The convergence metrics, Hypervolume, -Progress, and Generational Distance, for the Reference Problem Formulation, 50.000 NFE, and 5 seeds.