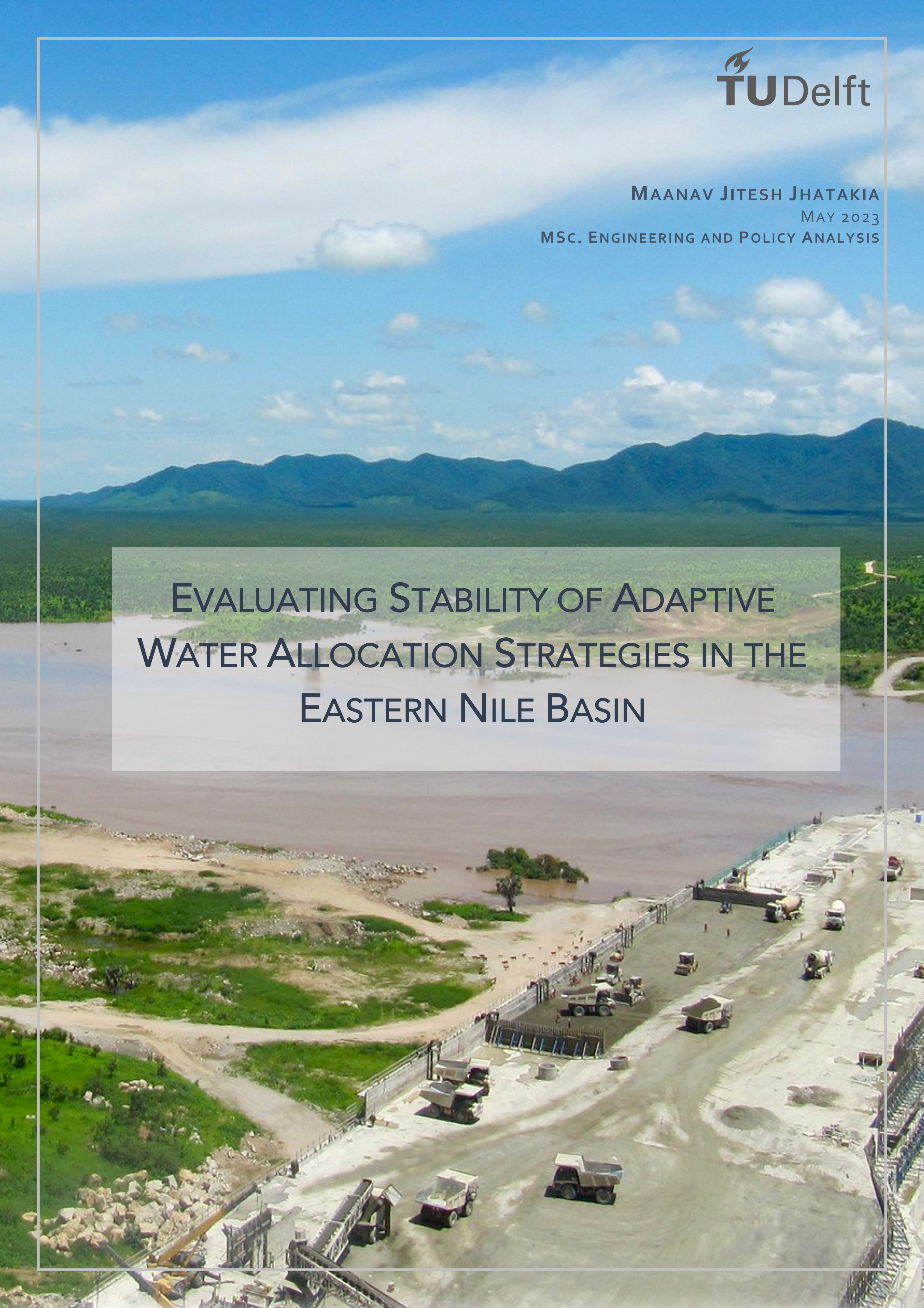

MAANAV JITESH JHATAKIA
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MSC. ENGINEERING AND POLICY ANALYSIS

EVALUATING STABILITY OF ADAPTIVE WATER ALLOCATION STRATEGIES IN THE EASTERN NILE BASIN

EVALUATING STABILITY OF ADAPTIVE WATER ALLOCATION STRATEGIES IN THE EASTERN NILE BASIN

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ABSTRACT

As the impact of climate change becomes increasingly urgent, conflicts over transboundary water resources have become more complex, particularly in light of the role of water in shaping socioeconomic and regional power dynamics. The challenge of optimizing objectives and strategic behavior across multiple stakeholders simultaneously makes it difficult to arrive at policies that can enhance long-term transboundary water management in a harmonious manner. In the Eastern Nile Basin (ENB), tensions have risen between upstream Ethiopia and downstream Egypt and Sudan due to the development of the Grand Ethiopian Renaissance Dam (GERD), making successful negotiations for water allocation critical. Ideally, such negotiations should produce agreements with high-stability policies, meaning that no actor has an appealing unilateral gain in utility that would cause them to defect from an agreement.

Several water allocation simulations have been developed in the ENB using both linear and nonlinear programs to aid decision-making, but only two studies have previously examined measures of stability for these optimization results, and neither has been done since the completion of the GERD. Moreover, as simulation complexity has increased, there is a gap in knowledge regarding the measurement of stability using optimization results from closed-loop, multi-objective adaptive simulations.

To address this gap, this research reexamines the stability of policy candidates for water allocations in the ENB using three different solution concepts from cooperative game theory—the Nash-Harsanyi solution, the Shapley value, and the nucleolus. The stability of each policy candidate is assessed using three different stability metrics—the Euclidean distance, the Loehman Power Index, and the propensity to disrupt—to determine their relative stability. The approach yields similar objective trade-offs and utility behaviors for the Nash-Harsanyi and Shapley Values. The most stable policies, when ranked by Euclidean distance, prioritize Ethiopia's utility, while policies become more unstable with the rapid growth of Egypt's utility. Furthermore, propensities to disrupt and power indices between Egypt and Ethiopia or Sudan show converging and diverging behaviors, respectively, which explain the negotiation potentials between the players. Our results indicate that Egypt's willingness to engage in collaboration is directly related to its level of utility; however, at these levels, Ethiopia and Sudan's benefits from utility are at levels that prompt higher likelihoods of defections from a potential coalition. The results also showed stable policies characterized with high policy efficiencies in instances of basin-wide cooperation, which increases benefits to all nations.

Given the different assumptions and characteristics of each stability concept, the insights on the stability of different policies provide general guidelines for incorporating stability into the optimization formulation itself. The results have larger implications for policy planners in the ENB and the difficulties they may face when finding acceptable solutions in multi-stakeholder decision arenas. Furthermore, the methodological contribution of this study could allow for easy application of this method to other water allocation conflicts to help guide policy planners detect opportunities for utility optimization or risk mitigation in a cooperative setting.

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In August of 2021, I relocated five thousand miles from Colorado to the Netherlands to start my adventure at TU Delft. It was an incredible change, pushing me out of my comfort zone to a country that I had always dreamed of living in. Just shy of two years later, I write this as my time at TU Delft is sadly wrapping up.

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1. INTRODUCTION

The severity of climate change is expected to increase in the future, leading to an overwhelming consensus that vital natural resources will become even scarcer. When multiple stakeholders rely on natural resource commodities, such resources are referred to as common-pool resources (CPR). These resources share two primary characteristics: high subtractability, which means that the usage of one stakeholder has a direct impact on the usage capabilities of others, and low excludability, which refers to the degree to which usage can be confined to an intended set of stakeholders (Ostrom et al., 2008). The critical use of CPRs in multiple industries has necessitated greater scrutiny of water allocations to different stakeholders. There is an agreement that conflicts surrounding commonly used resources, such as water and non-renewable resources, will increase due to their finite nature and necessity for the functioning of our societies and economies. In regions with pre-existing political and socioeconomic instability, water conflicts may exacerbate transboundary conflicts to levels not previously seen, as water is an existential resource.

The Eastern Nile Basin (ENB) is a well-established example that highlights the need for long-term water management strategies to alleviate existential conflicts. Ethiopia, Egypt, and Sudan have all had centuries of dependence on the Nile River for sustaining their populations and forming the region's socioeconomic and political foundation. Since the early 20th century, however, expansion efforts and growing populations have led to large conflicts between all three nations. For this analysis, we begin to 2011, when Ethiopia announced its intention to build the Grand Ethiopian Renaissance Dam (GERD), built along the Ethiopian-Sudanese border to dramatically increase hydroelectric power generation (with enough to export to neighboring countries). Its scale and the head (water pressure) necessary to fulfill Ethiopia's electricity generation goal has greatly worried Egypt and Sudan, who claim that a lack of flowing water will directly inhibit their nations' growths (Wheeler et al., 2018; Arsano and Tamrat, 2005).

As water resources continue to diminish, stakeholders must transition from using their previously allocated resources to staking a claim to benefit from CPR pools. Policymakers are thus required to engage in multi-objective decision-making in this multi-actor system, trying to optimize the distribution of the limited utility at their disposal (Read et al., 2014). Water management policies are typically designed for longer time frames due to the necessary infrastructural investments. Therefore, negotiations of these policies allow stakeholders to compete with others to maximize their own utility from a common water source (Hermans et al., 2014). However, CPR management has historically suffered from the *"tragedy of the commons,"* where non-cooperation between stakeholders in determining equitable and feasible allocations has led to rapid depletion (Madani and Dinar, 2012).

Consequently, researchers have often employed game theory to study conflicts in water resource management and understand the potential outcomes of negotiations. Game theory assumes rationality from individual agents or coalitions, and conflict outcomes can theoretically be determined by assessing stakeholders' strategic behaviors or simulating the rational choices of these individuals. Cooperative game theory (CGT) and non-cooperative game theory (NCGT) have both been used to model behavioral patterns between stakeholders. While CGT models find solutions with the highest cooperative gains, they have been criticized for treating stakeholders as one entity with a unanimous approach in each decision step (Dinar and Hogarth, 2015). On the other hand, NCGT has been used to showcase the conflict fueled by stakeholders who are certain of their objectives while attempting to deduce rival actions and their consequences.

In game theory, a solution is stable when all participating stakeholders have no unilateral benefit from defecting from an agreement or breaking the grand coalition, assumed to be the coalition with the highest worth. A policy's stability can indicate how cooperation can alleviate water conflicts between stakeholders and, by extension, lead to desperately needed long-term water management. There are various solution concepts in game theory (Madani and Hipel, 2011; Madani and Dinar, 2012). The use of one concept over others has not been clearly delineated. Furthermore, there are multiple stability metrics that have been used to gauge power dynamics, motivations for defections, and other approximate indicators of how successful water management negotiations may be. However, given the ENB's geopolitical context, the stability of candidate policies must be analyzed from multiple aspects to characterize policies that render a portfolio where ENB nations have little motivation to defect from a negotiated set of actions. Calculating different stability concepts in the ENB has been done previously by several authors (Digna et al., 2018; Dinar and Nigatu, 2013; Wu and Whittington, 2006). Their research, while testing a few solution concepts, made use of results from a more basic, open-loop optimization model.

Alternatively, our analysis will account for the major management changes and uncertainties (with regards to flow and other environmental factors) that will arise with the GERD's full operation. Second, our research uses outputs from the *Eastern Nile Optimization* model, a multi-objective and multi-stakeholder simulation model developed by Sari (2022). It incorporates an evolutionary directed search approach to ENB water management, which has the capability to adapt decisions based on previous simulation conditions. Thus, the Pareto-set of strategies that we assess are designed with regular recalibrations based on a variety of different environmental conditions. Furthermore, through this analysis, we create different framings of stability for each strategy with use of various stability metrics to ultimately help characterize the most stable policies for the ENB.

REPORT ORGANIZATION

Section 2 will include a thorough literature review along with background information on the ENB's conflict. This will also explore each actor's motivations and create the context for assessing the contextual stability of the policies. Research questions and the objective of this analysis will be formally defined here. Section 3 will then move into the methods, where the core research on CGT will be explored. Solution concepts, their assumptions, and their characteristics will be outlined along with stability metrics. Before this, a summary of the *Eastern Nile Optimization (*ENO) model, used to generate the Pareto-set in this analysis, will be given along with the *Evolutionary Multiobjective Directed Policy Search* (EMODPS) framework, which the ENO model employs to incorporate a unique adaptive search method to prior ENB simulation designs. Section 4 will define an experimental set-up, sensitivity analysis, and utility functions. Section 5 will show results. Section 6 will include a brief analysis of the interpretations and implications of the results but also look to highlight guidelines for stability analyses done in the future, including those that may wish to incorporate this earlier on in the multi-objective policy search process. Finally, Section 7 will briefly reiterate answers to the research questions, acknowledge limitations, and explore future work.

2. BACKGROUND

2.1 THE NILE RIVER BASIN

The Nile River, extending over 6,700 kilometers and covering an area of approximately 3.2 million square kilometers, is recognized as the longest river globally. It passes through a region that includes 11 countries with diverse climatic zones, collectively known as the Nile Basin, before discharging into the Mediterranean Sea in northern Egypt. The Nile Basin is home to approximately 257 million inhabitants, who are heavily reliant on the Nile River for their sustenance, primarily for agriculture, hydroelectric power generation, and human consumption. The river is fed by two principal tributaries, the White Nile, originating from upstream catchments in Rwanda and Burundi, and the Blue Nile, which arises in Ethiopia and flows through the Eastern Nile Basin, eventually converging with the White Nile at Khartoum, the capital of Sudan (Swain, 2011). While the Blue Nile accounts for almost 86 percent of the total Nile water, its high discharge volume and elevated upstream Ethiopian catchment endow it with considerable hydropower potential (Dumont, 2009). In this study, the emphasis is solely on the benefits derived from the Blue Nile stem and examines negotiations among Ethiopia, Sudan, and Egypt.

The reliance on the Nile River by the Eastern Nile Basin (ENB) dates back to ancient times. The hydrology of the Nile, which exhibits high inter-annual variability in rainfall and variations in flow velocities across the basin due to natural landscapes and water infrastructure (Wheeler et al., 2020), allowed for the transport of both water and nutrients to downstream states. This, in turn, enabled the development of a robust agricultural industry and the establishment of strong political states. As European expansion in the ENB increased, colonizers began advocating for a basin-wide management system (Hurst et al., 1947). Following Egypt and Sudan's independence, the desire for rapid industrial growth and Ethiopia's independence prompted the former to jointly create a 1959 Agreement to assert allocations of Nile water, which was not accepted by upstream Nile states (Mckennon, 2010). This event marked a turning point in Egyptian and Ethiopian bilateral relations, with tensions remaining high to the present day (Obengo, 2016). Meanwhile, Ethiopia has repeatedly expressed interest in taking advantage of its hydropower capabilities, most recently through the 2011 announcement of the Grand Ethiopian Renaissance Dam (GERD). With an installed capacity of 5150 Megawatts and an expected annual energy production of 16 Terawatt-hours, the GERD is Ethiopia's largest campaign in a series of dam constructions planned for the near future (Nars and Neef, 2016). It is expected to hold almost 88 percent of the annual average volumetric flow of the Nile (Kandeel, 2020). In more recent years, the exploitation of natural groundwater reserves for irrigation and consumption purposes, coupled with aggressive expansion campaigns in these countries, have significantly increased the demand for Nile waters, despite these nations not supplying any of the water in the river (Dumont, 2009).

The Declaration of Principles signed in 2015 was an attempt to ease tensions between Ethiopia, Sudan, and Egypt regarding the construction of the Grand Ethiopian Reneissance Dam (GERD). The declaration highlighted the primary purpose of the GERD as generating sustainable and reliable clean energy supply to alleviate the region's inequitable and insecure electricity access. Ethiopia acknowledged the "principle of no harm" to downstream states but also maintained its supposed right to adjust negotiated terms involving the GERD's operation with downstream notification. Despite prior attempts by Ethiopia to alleviate reservations from Egypt and Sudan, tensions remained elevated, with Egypt formally requesting mediation by a third party, such as the United States or United Nations, for any further negotiations with Ethiopia in the GERD's matter. Additionally, further research into the Declaration reveals that it perpetuates the main issue at hand of the equitable allocation of Nile water amongst the three primary players.

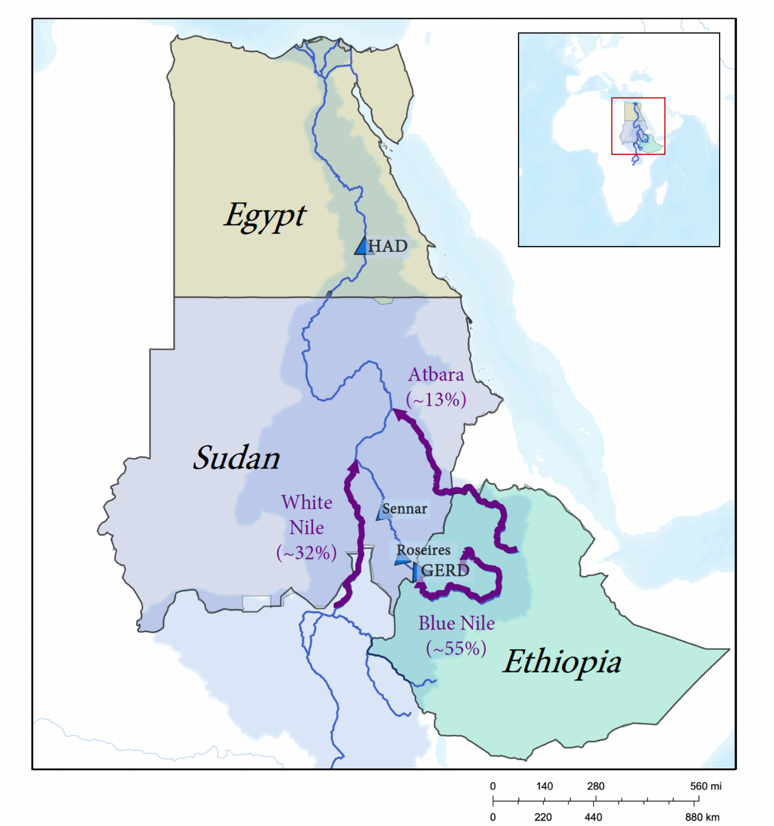


Figure 1: Geographic region of the Eastern Nile Basin with the location of the Grand Ethiopian Renaissance Dam and other major water infrastructure considered in this analysis. (original diagram from Sari (2022).

2.1.1 *Egypt’s Water Security Concerns*

Egypt has traditionally viewed water availability as a matter of national security. Historically, Egypt had benefitted from regular flooding of the Nile without significant interference from its neighbors. However, since Ethiopia's announcement in 2011 of its intention to construct the Grand Ethiopian Renaissance Dam (GERD), Egypt has been concerned about the anticipated water flow deficit and the potential implications for political and economic stability, for three main reasons.

Firstly, Egypt occupies a unique position in the Eastern Nile Basin (ENB) conflict, as it depends on the water use behaviors of upstream countries, while simultaneously boasting the largest economy in the Nile Basin. This economy is heavily reliant on the booming agriculture industry, which relies almost entirely on Nile surface water and already faces annual demand deficits of approximately 13.5 billion cubic meters (BCM) (Omar and Moussa, 2016). Despite the existence of groundwater reserves and reserve supplies in Egypt's High Aswan Dam (HAD), these resources have been rapidly depleted due to excessive usage for agriculture and consumption to offset deficits. This problem is likely to exacerbate with Egypt's rapidly increasing population, which is placing even greater pressure on all natural resources available.

Secondly, Egypt asserts that its electricity stability will be jeopardized by the GERD's operation. The HAD located in southern Egypt generates a significant amount of electricity for the country, contributing to the fact that most Egyptians are connected to electricity (Biswas, 2016). Additionally, the HAD facilitates flow regulation for irrigation and consumption purposes. As both the HAD and GERD are located on the Nile river, further constriction of volumetric flow could threaten the energy production requirements of the HAD (Strzepek et al., 2008). Thus, Egypt contends that the GERD constitutes a direct threat to its security.

Finally, Egypt faces socioeconomic and political instability following the 2011 Arab Spring Revolution, which led to high inflation and unemployment rates. The country's agricultural sector is a significant source of employment for its young population. A rapid acceleration in GERD's hydropower production, as expected in 2025, could result in Egypt losing nearly half of its arable land due to decreased water access (Farouk, 2022).

2.1.2 *SUDAN'S WATER SECURITY CONCERNS*

Sudan, much like its neighbors, operates a primarily agrarian economy and requires regular Nile water to grow its economy. Being physically in between the opposite representatives of the ENB conflict, Sudan took a unique position in the 1990s by balancing its own interests with maintaining cordial foreign relations with its neighbors to trigger any countermeasures and, thus, accelerate economic growth (Otinov, 2022). Despite changes in political power, Sudan has also emphasized the importance of regulating the main water source in the country in an attempt to sustain its agriculture and hydropower production.

Historically, Sudan and Egypt's alliance against upstream Nile states was strong. However, Egypt's demands to support its rapid growth often overshadowed Sudan's concerns, particularly surrounding the routine flooding that Sudan would experience from Ethiopia. Sudan's independence has wavered in the last few years following studies that conclude that water infrastructure activity in Ethiopia may provide some alleviation from these flooding events (de Falco and Fiorentino, 2022; Basheer et al., 2018).

2.1.3 *ETHIOPIA'S CONCERNS AND MOTIVATION*

Ethiopia's motivations for GERD are quite complex and are rooted in a desire to improve socioeconomic conditions for the nation. Ethiopia has a largely agrarian economy, with most of its citizens residing in rural areas. As such, less than a third of its population has access to electricity. Since the discovery of massive energy generation potential in the 1960s, the country has constructed small water infrastructure projects along the Nile to enhance its water catchments (and, by extension, its food security), due to the severe droughts that it periodically faces (Tawfik, 2019). The GERD is, therefore, the largest attempt so far by Ethiopia to try and achieve energy stability, but also leverage its position as an upstream state with robust renewable energy capabilities to eventually export energy to its neighbors.

The conflict with downstream neighbors is rooted in deep-seated mistrust and primarily arises from the hegemonic influence that Egypt has imposed in the region. As noted above, the 1959 Nile Water Agreement (and the preceding 1929 Agreement) effectively gave Egypt full blocking power over any projects in the Nile upstream. Both of these agreements were not recognized by Ethiopia, but Egypt has repeatedly threatened military power or other political countermeasures on Ethiopia's projects. The intensified conflict with downstream neighbors is also, in part, a product of large-scale international investment in the region. The GERD and several other infrastructure projects, for example, in Ethiopia and neighboring countries have been funded by China, as it looks to increase its investments in Africa (Pemunta et al., 2020). The United States, alternatively, started out as an observer, but exogenous interests have shifted the United States' role to being a power broker, including through the imposition of sanctions on Ethiopia to pressure against GERD development (Gramer, 2020; Pemunta et al., 2020).

2.2 Review of Foundational Research

A literature search in two different areas of relevance was conducted. First, research was done on the evolution of different frameworks and programming techniques used to develop simulation-optimization models, including those that have specifically been created for the ENB. This area of research forms the basis for Sari (2022)'s novel approach to finding a Pareto-set of policy candidates and, by extension, why a new stability analysis on policies generated from this novel approach needs to be conducted. Within this, changes in frameworks will also affect the model's internal structure, which will also affect objective value determination (Kwakkel and Haasnoot, 2019). The second angle of research specifically looks at the involvement of game theory in studying water allocation conflicts. This will include applications and assumptions. Combining the above two relevant areas should reveal what stability concepts we can use for this project, where gaps lie in stability analysis in the ENB, and how this stability analysis can contribute to decision support research.

2.2.1 *Evolution of Water Allocation Models and Decision-Support*

Guiliani et al. (2021) notes that most water management models, essentially volumetric balances, used a combination of linear programming and "rule curves" that predicted amounts of water release based on the time of year. However, the use of linear programming meant that these models did not consider changing environmental conditions for future "states of the world" (Zatarain Salazar et al., 2016). Furthermore, these simplified models broke down the aggregated system into sub-systems that were programmed but were confined to rules outlined for linear programming and other relatively simple analytical approaches (Bogardi and Nandalal, 2007). Because of these simplifications and a relative lack of public computational access, these modelling techniques were never really used in real world decision-making processes and remained in academia. Initial movement from rule curves and open-loop decision sequence formulations included the use of genetic algorithms, which acknowledged that despite potentially having pre-defined operating rules that have been negotiated between stakeholders, system operators will have to deviate from these rules given environmental circumstances. When also considering that the rigid structure existing in open-loop models without any feedback information meant a lost opportunity for high-quality solutions, varying environmental conditions needed be accounted for in the volumetric balance to bring an adaptive approach (Quinn et al., 2017; Oliviera and Loucks, 1997).

Genetic algorithms were extended with stochastic dynamic programming but, given its limitations of dimensionality and not being able to efficiently handle multiple objectives, alternative problem formulations were chosen (Guiliani et al., 2016). Additionally, as realizations of the sheer amount of information needed to properly model water systems came to light, there was also a recognition for models that incorporated anticipatory capacities to aid in long-term simulations (Guiliani et al., 2015). To address this, closed-loop designs have relatively recently been used, which are dependent on previous system states and thus require a feedback structure. Finally, it is clear that most water allocation models primarily had mathematical foundations, and any representation of stakeholders in this process was solely through a pre-defined set of objectives and a direction of preference for purposes of optimization. As such, despite growing interest for participatory model processes, most models did not entirely incorporate this (Soncini-Serra et al., 2007).

With respect to the ENB, there was a shift in the literature, with the introduction of the GERD, from purely mathematical optimization to multi-stakeholder, multi-objective decision-making. The optimization model techniques followed the progression described above; however, there was also a noticeable split in research, as the ENB case study become one to analyze the effects of non-cooperative strategies. Whittington et al. (2005) created the *Nile Economic Optimization Model* (NEOM), employing linear programming to find optimal monetary allocations to ENB nations. Goor et al. (2010) improved this by applying stochastic dual-dynamic programming (SDDP) the ENB, but despite determining efficient allocations in various scenarios, it does not repeat evaluations to see whether these allocations (1) are applicable under other environmental conditions, and (2) are accepted by the ENB's stakeholders. The same limitations were observed with Arjoon et al. (2014)'s use of SDDP to perform a risk assessment in the ENB, assuming full operation of the GERD and full cooperation between all nations. Digna et al. (2018) used a genetic algorithm-based optimization model to find optimal operation strategies in the ENB. In their analysis, they run rival problem formulations with both CGT and NCGT, where the CGT scenario treats the ENB as one entity rather than (primarily) three separate countries. Stamou and Rutschmann (2018) used a Nexus approach with a parameterization-simulation-optimization model to interconnect water, energy, and food in finding a Pareto set of optimal solutions. Wheeler et al. (2016, 2018, 2020), whose work has inspired the optimization model used in this study, published several studies that modeled the ENB and focused on operational challenges using multi-objective optimization.

Several studies from Mohammed Basheer and collaborators have also focused on water management decision-making frameworks for the ENB. Basheer et al. (2018) also studies the Water-Energy-Food (WEF) Nexus and its effects from cooperative strategies on the Blue Nile. It investigates hydrological dynamics between the GERD and Sennar Reservoir in Sudan based on irrigation water demand, water allocations, and a constraint from annual rainfall data. Most recently, Basheer et al. (2023) introduced a framework specifically for adaptive water management in the ENB. The developed model optimized nine objectives and incorporated various climate projections, hydrological system components, and economic indicators to identify opportunities for ENB economic growth. The model placed adaptive constraints on GERD operations based on downstream conditions, ultimately demonstrating benefits for economic and resilience growths if cooperative compromise across ENB nations is chosen.

Overall, ENB simulations have certainly grown in complexity, but only quite recently have studies adopted simulation use rather than just optimization algorithms. More recently, evolutionary algorithms have allowed for higher functional evaluations in multi-objective optimization (Hadka and Reed, 2013). This also meant that greater volumes for scenario discovery can be made, and optimizations can be designed so that different policy levers are used depending on performance metrics. Thus, we can combine the use of evolutionary algorithms with the increased knowledge capacity that simulation usage gives to model a highly complex hydrological system like in the ENB. It allows for a high-quality set of solutions to emerge, significantly benefitting policymakers (Quinn et al., 2017).

Lastly, post-optimization decision support follows the optimization process and is when stakeholders can negotiate to come to an agreement on policy(ies). Decision support forces a shift from *a priori* decision-making, where stakeholders have objective preferences based on assumptions of which “states of the world” are plausible. It shifts to *a posteriori* decision-making where trade-offs between objectives and robustness metrics inform stakeholders about preferences regarding objectives (Kwakkel and Haasnoot, 2019). However, in most studies, if present, decision support was primarily a discussion of the tradeoffs observed from the Pareto set without much re-evaluation of analysis done specifically on those solution(s). Effectively, these studies highlighted trade-offs without much discussion on long-term operational or policy implications. Gold et al. (2022)’s use of *regional defection analysis* (RDA) post-optimization to analyze robustness conflicts between stakeholders in the Sedento Valley was an exception because focus was placed on understanding power dynamics in multi-actor systems.

2.2.2 *PRIOR USAGE OF GAME THEORY*

Both CGT and NCGT have been previously applied in transboundary water conflicts. Within game theory, there also is a distinction between transferable (TU) and nontransferable utilities (NTU), where TU games assume the possibility to transfer utility (benefit) linearly from one stakeholder to another, usually due the use of a commonly traded utility like cash (Peters, 2003). NTU games have also generally been situations where stakeholders intend to engage in non-cooperative behavior to increase their own benefit (Teasley and McKinney, 2011). Madani and Dinar (2012) and Madani and Hipel (2011) wrote extensive reviews on various stability concepts for CGT and NCGT, respectively. While CGT has seen limited use in real life in transboundary water basins, many studies have used CGT with the intention of showing possible distributions of the increased benefits that come from cooperation (Teasley and McKinney, 2011; Wu and Whittington, 2006). In most water systems, including the ENB, the shared resource implies that a cooperative strategy will be necessary (Madani and Dinar, 2012). Thus, working with a cooperative motivation could eventually help all parties.

Alternatively, NCGT has primarily been used mainly in a normative manner to show problems that may occur as a result of no cooperation. Elimam et al. (2008) used pre-defined strategy preferences of fighting ENB stakeholders to find probable outcomes using the graph model for conflict resolution (developed by Fang and Hipel, 1993), after which a brief sensitivity analysis was done. While a different approach, the end goal for this is the same in determining stable outcomes, which is to inform policy holders of strategic behaviors and actions. Ding et al. (2016) also used a non-cooperative foundation in their study in the Nile Basin. To simulate the individual maximization of benefits from water allocation and show negative effects of centralized system techniques, they employed agent-based modelling along with a developed evolutionary search algorithm to identify equitable allocations based on the nation’s ultimate economic contribution to the system. Use constraints were added to try and incorporate fairness by accepting that each nation’s acts would be selfish by nature. Mehrparvar et al. (2020) also used the graph model for an Iranian water utility, but this study mainly was a methodological contribution to the graph model as it found which scenarios best predicted consumer water demand.

There have been studies where different CGT solution concepts have been used together in comparison. However, most studies have stuck to using the main solution concepts of the Shapley Value, Nash equilibrium, and Nucleolus. Dinar and Howitt (1997) use CGT stability concepts to optimize joint environmental cost distribution among contributors of the drainage pollution problem in California. The concepts included a proportional allocation, the Nash-Harsanyi equilibrium, the Shapley value, and the nucleolus. Both Wu and Whittington (2006) and Dinar and Nigatu (2013) applied CGT to the ENB, using the same set of stability concepts, although the 2006 study does this to find cooperation-incentive opportunities assuming non-cooperative intentions. A linear programming for transboundary conflicts on the Euphrates and Tigris Rivers also used the core and Shapley value calculations to find stable (or Nash equilibrium) water allocations between Turkey, Syria, and Iraq (Kucukmehmetoglu and Guldmann, 2004). They note a common reason for using different stability concepts (or “allocation schemes”), in that policies that are not in the game theoretical Core (discussed in Section 3.3.2) can theoretically not be considered absolutely stable. Therefore, to account for differences in judgement of using one concept over another (and different assessments of fairness), a variety are used; this logically follows that policies that are stable across multiple concepts are thus the most stable of the optimized set (Madani and Dinar, 2012).

Stability metrics have mainly been defined either in the context of game theory applications or in mathematical literature. Bargaining power was also assessed in Madani et al. (2022), where differently weighted CGT schemes were assessed for the Caspian Sea transboundary conflict to assess the Core’s constituents using the same solution concepts from Dinar and Nigatu (2013). The 2022 study follows up on Read and Madani (2014)’s study, where an economics-based power index method was used to predict a stakeholder’s willingness to negotiate with neighbors rather than abstaining. Mirzaei-Nodoushan et al. (2022) also used a measurement of the harm to a coalition in the event of a defection, later determined to be Gately’s *propensity to disrupt.* Overall, most studies only made use of a single stability metric as an index to determine the stability of a set of possible solutions.

2.3 RESEARCH OBJECTIVE

The research objective is to analyze different methods of determining the relative stability of solutions in the Pareto-optimal set using various stability metrics and different CGT solution concepts as reference solutions. In the case of the ENB, Nile water is a shared resource that is crucial to the political and socioeconomic integrity of the region. Despite the GERD's operation causing controversy, negotiations between the riparian neighbors through the Nile Basin Initiative (NBI) are ongoing, indicating a concerted effort to build a cooperative and long-term strategy (Basheer et al., 2023). By incorporating CGT with stability and comparing behaviors across the entire Pareto-set, we can assess the relative stability of a policy candidate rather than its absolute stability. This research aims to characterize stability in the optimized solutions in the Pareto-front so that decisions can be made from those policies that optimize the nations' incentives to cooperate. Analyzing different stability concepts for the ENB will also contribute to a methodological approach to decision support in studying the feasibility of adaptive water policy management in the ENB under geopolitical constraints. This can further contribute to research on implementing stability and fairness concepts into the optimization formulation as an objective.

2.4 RESEARCH QUESTIONS

Given the research gaps above, the following research question and sub questions are posed. Sub-questions are derived to systematically answer the main question at hand.

How can the stability of different Pareto-front policy candidates be relatively assessed in the case of the ENB?

(a) *What are different concepts of stability that can be applied in cooperative game theory, and what are the assumptions and characteristics of each concept?*

(b) *How do distributional outcomes and trade-offs experienced by ENB stakeholders differ between the baseline optimization and different solution concepts and stability metrics?*

(c) *How can the results from the stability analysis on the ENB inform the enhancement of an optimization formulation to include stability as an optimizing objective from the onset?*

Although the ENB serves as a case study, the research (sub)questions formulated above are grounded in theory. While prior literature incorporating CGT has done so while applying various transboundary river basins as examples, their focus on geopolitical context and limited interpretation of solution concepts' feasibility has been criticized. Our analysis aims to expand the application of CGT by prioritizing stability analysis. The theoretical aspect of our research question seeks to establish a method of assessing stability across different policy candidates that can be adapted to conflicts over common-pool resources. The ENB serves as a high-profile case study that has been extensively studied before and can benefit from the critical negotiations that continue to take place due to its geopolitical and environmental implications. Research sub-question (b) is the most specific to the ENB because regional context is crucial to interpreting the method's results on a case-by-case basis.

3. METHODS

This analysis focuses on providing post-optimization decision support. Therefore, the methods used in this analysis are combination of mathematical research, the prior usage of stability metrics in coalitional games, and their eventual application to the performance outputs of the *Eastern Nile Optimization* model.

3.1 THE EMODPS FRAMEWORK

Considering the increased stress on water resources as a result of growing populations and increasingly severe climate change effects, water resource management teams globally are encountering more resistance to new infrastructure development. In addition to being due to environmental considerations, significant pushback is due to inadequate amounts of flowing surface water needed to generate acceptable economic returns on large-scale investments. As such, retrofits to current operations and capacity expectations must be prioritized to utilize hydrological power more efficiently (Gleick and Palanaippan, 2010). To redesign operation policies, two different solution methods have historically been used (specifically in application to water resources research). One of these methods, stochastic-dynamic programming (SDP), employs an evolutionary strategy of a decision-making process, where the decision taken at time t, and the performance metrics that showcase this decision, will influence the state of the system in all subsequent iteration steps (Guiliani et al. 2016). Guiliani et al. (2016) notes, however, that real-life adoption of SDP has been limited. One hurdle is the exorbitant acceleration of computational cost with high dimensionality (the *curse of dimensionality*). The second hurdle is the requirement for incorporating high amounts of information to predict a sequential decision-making simulation's next *state* (*the curse of modeling*). Finally, the *curse of multiple objectives* is where increased complexity of a simulation (via the inclusion of more than one objective) would trigger a trade-off with computational expense and accuracy of the Pareto-front set of policies.

To this effect, a policy search formulation is needed that is capable of handling increasingly complicated simulations while also adapting its operating policies based on pre-defined metrics. The directed policy search (DPS) is therefore used, of which the *Evolutionary Multiobjective Direct Policy Search* (EMODPS) framework is one approach. DPS parameterizes an operating policy and the parameter space to find a parameterized policy that will optimize performance metrics (Zatarain-Salazar et al., 2016). The EMODPS methodology shown in Figure 2 will implant a non-linear approximation network (such as a radial basis functions) as a policy function into the simulation. With every time-step of each run, the policy function will calculate a decision (such as release amounts) based on an evaluation of the system's state at that time. Essentially, the policy function adjusts its executions to optimize a model's metrics while the policy function's parameters are improved by a multi-objective evolutionary algorithm (MOEA).

The barriers to SDP usage listed above are all addressed with the EMODPS framework. Computational cost is fairly controlled in the framework's iterative approach as it does not compute value functions for each state-decision variable combination (Guiliani et al., 2015). More importantly, the use of the EMODPS framework, thus, provides a Pareto-set of policy candidates that are products of changing state conditions in the model. Thus, compared to historically used open-loop problems that did not incorporate system feedback, these are stronger policy candidates that are more applicable for long-term water management planning across multiple infrastructural points (Quinn et al., 2019).

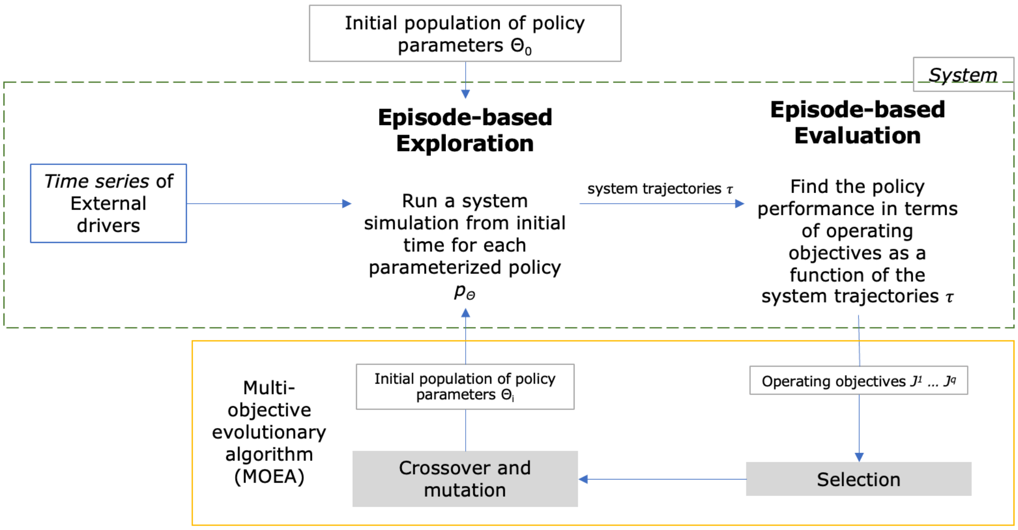


Figure 3.1: A EMODPS Framework Schematic showing the movements between the system of interest and the MOEA used to regenerate more accurate policy parameters (obtained from Guiliani et al., 2015).

3.2 Eastern Nile Optimization Model

The stability analysis is performed upon results emerging from the *Eastern Nile Optimization (ENO)* model, a Python-based multi-objective simulation model developed by Sari (2022). The model's scientific foundation is heavily based on research from Wheeler et al. (2018, 2020) on exploring cooperative water management strategies in the ENB. Sari (2022) combined this with the EMODPS framework to create a closed-loop model.

Figure 3.1 details the topology of this model. The model has a simulation timeline using a monthly time step from 2022 to 2042 (or a total of 240 months). As a brief overview, the model essentially simulates Nile river flow at various decision points. There are several components in between within the model where these inflow and release decisions are made. Irrigation districts divide the ENB into smaller regions that have water demands (for consumption or irrigation). While Sudan has five different irrigation districts, Egypt is designated as one large district. Four reservoirs are modeled: the GERD in Ethiopia, the Roseires and Sennar Reservoirs in Sudan, and the HAD in Egypt. Physical system constraints, hydroclimatic data, and water demands for different districts were used for this model. Operational and physical constraints were obtained from Wheeler et al. (2016, 2020). While hydropower is produced at all reservoirs, only production for the GERD and the HAD are evaluated.

As the *ENO* model simulates a physical system, it was developed as a *mechanistic* model (Soncini-Serra et al., 2007). The overarching mechanism is gotten a volumetric balance equations that incorporate past system conditions. In the beginning of month $\tau + 1$, to model the storage volume of a reservoir denoted as k, the following volumetric balance equation is used.

$$S_{\tau+1}^{k} = S_{\tau}^{k} + \int_{0}^{1} f\left(S_{\tau+t}^{k}, q_{\tau}^{k}, e_{\tau}^{k}, u_{\tau}^{k}\right) dt \qquad (3.2.1)$$

where S_τ^k denotes the storage volume of a reservoir in the beginning of the month τ. Calculating $S_{\tau+1}^k$ requires S_τ^k to be added to the change in storage volume over our time index, which is represented by a function f with parameters of prior storage volume, inflow (q_τ^k), evaporation rate (e_τ^k), and a release decision (u_τ^k).

Radial basis functions were chosen as the policy structure, which would ultimately determine where releases would take place. Reservoir storage and catchment inflow values serve as inputs into the policy function to inform about the system's present state. A network of weighted Gaussian radial basis functions (RBFs) was used as the function that calculates release decisions at each reservoir. After running input variables through each RBF function, we would calculate a single Gaussian RBF. From there, weights are applied to each RBF, and the weighted sum determines the release decision. The release decisions can be given as the following, slightly modified from Guiliani et al. (2020):

$$u_\tau^k = \sum_{i=1}^{n} (w_i^k \varphi_i \left(S_\tau, \sum_p Q_{\tau-1}^p, \tau \; mod \; 12 \right) + \alpha_k) \tag{3.2.2}$$

where w_i^k is the weight of the RBF, φ_i is the RBF formula, and α_k is a constant adjustment parameter for a particular release decision at a reservoir location. Note that physical constraints on the different reservoirs will also be considered in release decisions.

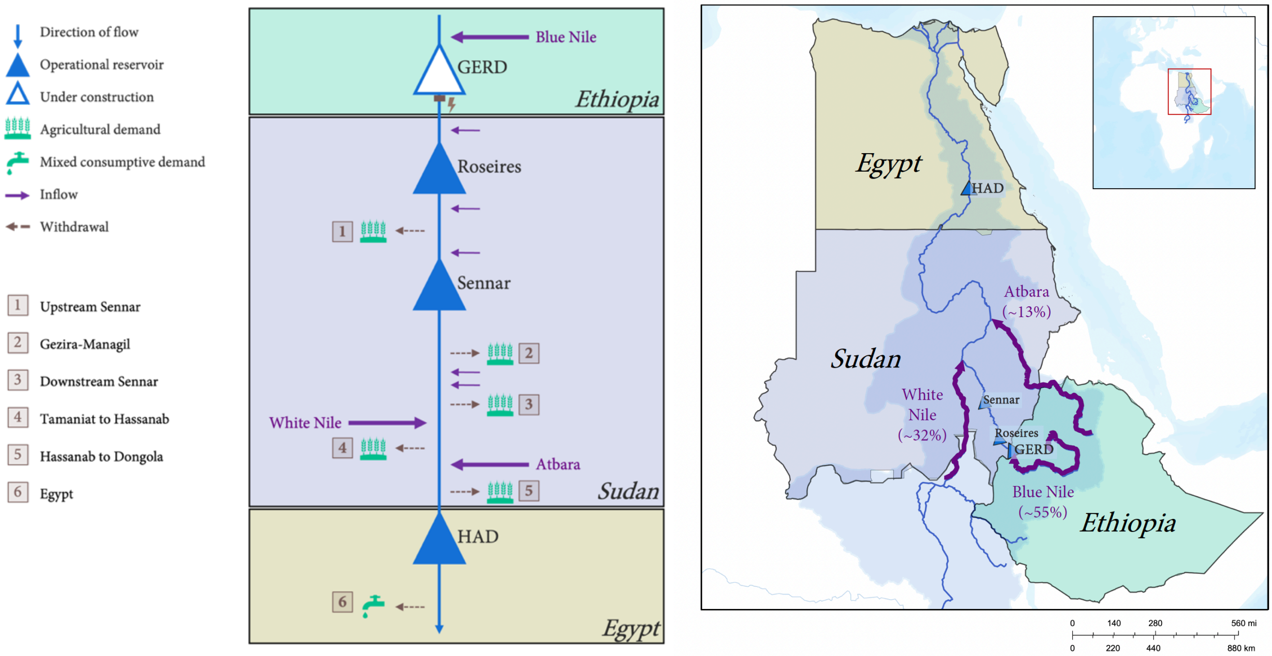


Figure 2.2: (a, *left*) A topology of the conceptual model used in the *Eastern Nile Optimization* model with (b, *right)* a reprint of Figure 1 to show a complementing geographic representation (both figures obtained from Sari, 2022). Note the difference in orientation between the two figures. Each of the infrastructure locations and the numbered irrigation districts in the topology graphic are decision points in the model, the decisions for which will be determined by the policy function and executed using policy levers.

Ten RBFs are used and a total of 164 free parameters that form the system's present state are optimized at each decision step using an ε-NSGA II evolutionary algorithm to enhance search diversity (Zatarain-Salazar et al., 2016). The optimized parameters (outputs from the algorithm) are than fed back into the policy function for the next evaluation. Finally, as the volumetric balance for each reservoir continues to evolve, their benefit to each nation is translated into a set of objectives pre-determined by the nations. At the end of the simulation's time frames, the integration of each release decision and its translation into the set of objectives, together, make a policy in the Pareto set. The model assumes a central authority with complete information on the system's state, thus allowing for coordinated release decisions. This implies that a coalitional framing would be logical when trying to find possible allocations.

The critical parts for this stability analysis are the *ENO* model's objectives which it uses to show outcomes of the model's optimization. The relevant objective functions and their directions of preference are as follows, taken directly from Sari (2022).

1. **Minimize irrigation demand deficit (Egypt)**:

$$\frac{1}{20}\sum_{\tau=1}^{240} max\left(0, D_{\tau}^{Egypt} - V_{\tau}^{Egypt}\right) \tag{3.2.3}$$

   with D_{τ}^{Egypt} being the water demand and V_{τ}^{Egypt} is the water received via the Blue Nile for a given month τ. This difference is calculated over the simulation lifespan and then divided to obtain an annual average. This objective produces a value in units of *BCM* per year. From hereafter, this will be referred to as Egypt's *irrigation deficit* value.

2. **Minimize the frequency of HAD low-water levels (Egypt)**:

$$\frac{1}{20}\sum_{\tau=1}^{240} HAD_{\tau} \tag{3.2.4}$$

$$HAD_{\tau} = \begin{cases} 1, if\ h^{HAD}(storage\ level) < h_{min}^{HAD} \\ \quad 0, otherwise \end{cases}$$

   where $h^{HAD}(storage\ level)$ is the head level of water at the HAD and h_{min}^{HAD} is the minimum water head level of 159 meters above sea level (Sari, 2022; Wheeler et al., 2018). This objective is ideally minimized and produces a decimal with a maximum value of 1 (representing 100 percent). Since electricity connectivity is integral to Egypt's functioning, Egypt would ideally look to minimize this frequency so that hydropower generation is guaranteed. For the purposes of this calculation, Egypt would not be considering impacts from irrigation deficit objectives.

3. **Maximize GERD hydropower production (Ethiopia)**:

$$\frac{1}{20}\sum_{t=1}^{240} P_{\tau}^{GERD} * d\ (\tau \bmod 12) * 24 \tag{3.2.5}$$

   where $(t\ mod\ 12) * 24$ is the number of hours in a specific month τ. P_{τ}^{GERD} is the hourly power output and is a function of the height of the GERD's turbines, the efficiency of the

GERD's hydropower generation process, the inflow that generates a maximum rotational velocity for the turbine, and the gravitational constant. This objective is ideally maximized and produces a value in units of *Terawatt-hours (TWh) per year.* From hereafter, this will be referred to as Ethiopia's *hydropower production* value.

4. **Minimize irrigation demand deficit (Sudan)**:

$$\frac{1}{20}\sum_{t=1}^{240}\sum_{j \in SD} max\left(0, D_{\tau}^{Sudan} - V_{\tau}^{Sudan}\right) \tag{3.2.6}$$

In the model, instead of one joint irrigation district being represented in Egypt, Sudan has a set of multiple irrigation districts, together denoted as *SD*. Other than this difference, the calculation of this objective is identical to the Egyptian analog. This objective is ideally minimized and produces a value in *BCM* per year. From hereafter, this will be referred to as Sudan's *irrigation deficit* value.

Sari (2022)'s model also incorporated two other objectives: the **90th percentile worst monthly irrigation demand deficit (Egypt)** and the **90th percentile worst monthly irrigation demand (Sudan)**. When running the model, we used the same formulation used in Sari (2022)'s original research and therefore optimized for all six original objectives. However, when performing the stability analysis, these two objectives would have been redundant in their inclusion to the utility conversions (due the irrigation-related objectives for both nations) and thus were not used.

3.3 COOPERATIVE GAME THEORY SOLUTION CONCEPTS

In CGT, we form a grand coalition because each player's benefit is maximized by doing so. Therefore, the challenge remains on how to properly distribute the grand coalition's characteristic value for all players in accordance with the Efficiency constraint. To do this, CGT has several *solution concepts*, or possible vectors that indicate an amount of utility allocated to each player. Each solution concept has underlying assumptions, calculation complexity, and value constraints that contribute to the development of the vector. Furthermore, the quantitative and qualitative parameters of each solution concept also reveal a different fairness regime that governs its interpretation (Deng and Papadimitriou, 1994). Because of these differences in fairness, various solution concepts were chosen for this analysis. The solution concepts used in this analysis were chosen as they previously have been applied to water allocation conflicts.

3.3.1 *CORE*

The Core has origins in microeconomic theory; Edgeworth (1881) first described the mathematical idea of a Core as the *contract curve* (also called the *Pareto set*), where a set of points that represent final commodity values between different parties are the result of mutually beneficial trading. The modern definition of the Core was introduced by Gillies (1959) and is a relatively simple concept of defining stability. The Core is the solution space for all acceptable allocations, or the set of allocations where no player within the game has a motivation to deviate due to a unilateral gain in utility (Madani and Dinar, 2012). In other words, the Core becomes the region where allocations, cumulatively, cannot be dominated by the formation of a sub-coalition.

When defining a coalitional game $G(N, v)$ with N players and corresponding worth functions v, we desire full cooperation between all players. Thus, the grand coalition (and by extension, its worth $v\{N\}$) must be attractive enough where no player has a motivation to deviate from said coalition. We assume that the game is made of players with bounded rationality are all looking to maximize their individual payoffs. Thus, they would only perform this action if there were an added benefit to all by working in a coalitional setting, also called *superadditivity*. Thus, the Core is defined as

$$Core\ (G) = \left\{ \omega \mid \sum_{i \in s} \omega_i \geq v(S)\ \ for\ all\ s \in S, S \subseteq N \right\} \tag{3.3.1}$$

where each allocation vector ω satistfies both *individual rationality* and *efficiency* requirements. Additionally, $N = \{1 \ldots n\}$ players in a game, and s are a set of members in a coalitional subset of the subset of all possible coalitions S.

Individual rationality entails that the allocation that a beneficiary receives under a cooperative agreement must be greater than or equal to the allocation that they would have received in a non-cooperative setting (Equation 3.3.2). The *efficiency constraint* places a limit on the total obtainable benefit allocation from the group setting, where all benefits must be distributed amongst all the members of the grand coalition (Equation 3.3.3). Equation (3.3.1) above incorporates the *group rationality* condition, a third condition, where the sum of any allocations in a coalitional setting must be larger than the worth value of that specific coalition. The boundaries that satisfy both individual and group rationality are called *imputations*.

$$\omega_i^* \geq v\{i\} \tag{3.3.2}$$

$$\sum_{i \in C} \omega_i = v(N) \tag{3.3.3}$$

Even if an allocation is present within the Core's bounds, it does not automatically imply that this allocation is a stable solution. Being in the Core (or *Epsilon*-Core, as discussed later) are only requirements for allocations to be accepted by the game's players solely on the grounds of allocation amount (Shapley, 1971). Solving the system of non-linear inequalities formed from equations 3.3.1-3.3.3 may prove that the Core is empty, meaning that there lacks a unique allocation that will satisfy all players' demands.

3.3.2 *EPSILON (ε)-CORE*

The *Epsilon*-Core is an extension of the Core to determine near-Core allocations. The ε-Core was applied to the *n*-player game theory framework by Wooders (1983), who discovered that *convexness* of the game, superadditivity, and *per-capita* boundedness are the requirements for ensuring that the ε-Core is a non-empty space. In the event that the Core is empty, we must find approximately acceptable allocations to identify a competitive equilibrium because some coalitions may actually prefer to break away from the grand coalition to reap larger rewards. The dimensions of Core will therefore have to be expanded out to include these approximate solutions. The dimensions of this expansion are determined by calculating the deviation incentive that these different players would have so that the incentive to join a coalition has a direct relationship with the coalition's size (*convexness)* (Ozyurt, 2021). To do this, we can subtract the deviation incentive ε from the characteristic values of each coalition. For a value $\varepsilon > 0$,

$$\varepsilon - \ Core\ (G) = \left\{ \omega \mid \sum_{i \in s} \omega_i \geq V(S) - \ \varepsilon\ for\ all\ s \in S, S \subseteq N \right\} \tag{3.3.4}$$

Equation 3.3.3 still holds for the ε -Core; however, the deduction is also done to individual rationality constraints. By implanting the equation modification to the system of non-linear inequalities above, the solution is a set of inequalities that extend the Core's bounds and thus provide a space for an acceptable solution. The deduction of ε can be thought of as a "tax" on each player's eventual allocation in order to prevent deviation; thus, the aim is to try and find the minimum value of ε, also called the *least Core*, whose formal definition is Equation 3.3.5.

$$\varepsilon^*(G) = \inf\{\varepsilon > \ 0 \mid \varepsilon - Core\ of\ G\{N, v\}\ \neq empty\} \tag{3.3.5}$$

3.3.3 *SHAPLEY VALUE*

The Shapley Value is one of the fundamental solution concepts in CGT. It was first introduced by economist Lloyd Shapley in 1951. The symmetric Shapley Value is a method for finding a fair and efficient allocation based on the weighted average of the marginal contributions of a particular player in the grand coalition. As such, the Shapley Value can provide a qualification of a player's strength in a coalition. This weighted average is done across all possible coalition sequence combination, with the total number of possible grand coalition sequences (with *n* players) being 2^{n}.

To calculate the Shapley Value ϕ_i of a specific player *i*, we take any coalitional game $G\{N, v\}$, where a player $i \in N$. The symmetric Shapley Value of a player i is the following :

$$\phi_i(N, v) = \frac{1}{n!} \sum_{\substack{S \subseteq N \\ i \in S}} |s|! * (n - 1 - |s|)! * [v(S \cup \{i\}) - v(S)] \tag{3.3.6}$$

where N is the makeup of the grand coalition, S is the sub coalition that contains elements from the grand coalition, $|S|$ is the number of elements in coalition S, and the value of $v[(S \cup \{i\}) - v(S)]$ is the marginal contribution of player *i* to the coalition S. There are four axioms that form the theoretical foundation of the Shapley Value. They are the following:

1. **Efficiency**: The Shapley Value follows the Efficiency condition of the Core.

   $$\sum\nolimits_{\boldsymbol{i} \in \boldsymbol{N}} \phi_i(N, v) = v(N) \tag{3.3.7}$$

   Specifically, the Shapley Values of all players, when added together, must be equal to the value of the grand coalition.
2. **Symmetry:** While the Shapley Value uses weighted probability, the probability weights of each player being in a coalition are *symmetric* or considered equal. If, for players *a* and *b,*

   $$v(S \cup \{a\}) = v(S \cup \{b\})$$

   then they will each have the exact probability of entering a coalition, regardless of the order of entry.
3. **Linearity:** The Shapley Value of a coalitional game is, atleast, the combination of allocations from the individual, non-cooperative games. Thus, expected payoffs will remain constant.
4. **Null coalition:** The Shapley Value of the *null* coalition (a coalition with no players) is zero.

One of the Shapley Value's assumptions is symmetry. Based on different political or contextual conditions, this assumption may prove to be untrue (Wu and Whittington, 2006). Therefore, Frye et al. (2020) introduced the asymmetric Shapley Value as a method of incorporating real-world knowledge (in this analysis's case, different problem formulations) to eliminate the probabilities of certain coalition permutations, thereby also eliminating the symmetry assumption. This would be done by assigning probability weights based on each player's perceptions on the likelihood of coalitions forming. This would require a quantification of geopolitical relations, actor perceptions, and other information related to the multi-actor dynamics in a game.

$$\phi_i'(N, v) = \sum_{\substack{S \subseteq N \\ i \in S}} r_i(S) * [v(S \cup \{i\}) - v(S)] \tag{3.3.8}$$

$$\sum_{i \in T} \sum_{T \subset S} r_i(S) = 1$$

where $r_i(S)$ are probability weights that a player *i* will join a coalition *S*.

Based on its mathematical structure, the Shapley Value can employ both marginalist and egalitarian theories of fairness. The marginalist theory shows one potential disadvantage as allocations determined by the Shapley Value would be based on a player's performance in a coalition. Therefore, large differences in characteristic value magnitudes, which would activate a marginalist approach, may skew the solution's allocation distribution. Additionally, the Shapley Value is not required to reside in the Core, even if the Core is non-empty. As such, there are no bounds of individual or group rationality on the Shapley Value. Shapley Values have been applied in a variety of different fields, most notably in feature selection and machine learning.

3.3.4 *NASH-HARSANYI SOLUTION*

The Nash-Harsanyi Solution is a modified solution concept in CGT. Its precursor, the Nash bargaining solution, was proposed by Nash (1950) as a solution to a 2-person game on how to allocate jointly earned utilities. Within a feasible set S, there exists disagreement points d_i for each player i, which is the minimal utility value that will be accepted (assuming that these utilities are *Neumann-Morgenstern* utilities that are maximized). Nash (1950) noted that a solution that will distribute total utility across two players is the allocations that maximize the produce of the players' payoffs. Harsanyi (1959, 1963) extended the Nash bargaining solution to an *n* – player game:

$$\Omega(S, d) = argmax\left[\prod_{i\,\epsilon\,N}(u_i - d_i)\right] \text{ where } (u_1, u_2)\ \epsilon\ S \text{ and } u_i \geq d_i \qquad (3.3.9)$$

where u_i is the Nash bargaining allocation to each player i. The Nash-Harsanyi solution, therefore, will be the set of allocation elements $(u_1, u_2 \ldots u_n)$ that will maximize the product of the differences between an allocation and each nation's disagreement point. The Nash-Harsanyi solution tries to satisfy the following axioms, outlined by Rubenstein et al. (1992):

1. **Symmetry**: The bargaining weight of each player is assumed to be the same; thus, if $d_1 = d_2$, then utility allocations to each player must also be the same.
2. **Invariance to positive affine transformations**: a solution is independent of any positive affine transformation of an original utility (where transformed utility $U' = a + bU \mid b > 0$).
3. **Pareto optimality:** There does not exist another allocation within the feasible set *S* that Pareto-dominates the optimal allocation.
4. **There is independence of irrelevant alternative allocations.**

There also exists an asymmetric modification of the Nash-Harsanyi solution $\Omega'(S, d)$for each player that relaxes the symmetry assumption. This is done through incorporating α_i , or the bargaining weight of a player i in the grand coalition (Harsanyi, 1982).

$$\Omega'(S, d) = argmax\left[\prod_{i\,\epsilon\,N}(u_i - d_i)^{\alpha_i}\right], \text{where } \sum_{i=1}^{n}\alpha_i = 1 \qquad (3.3.10)$$

By attempting to maximize both individual and group payoffs, the Nash bargaining solution uniquely attempts to balance egalitarian and utilitarian theories of fairness in the solution (Rachmilevitch, 2022; Shapley, 1967).

3.3.5 *NUCLEOLUS*

The nucleolus is another solution concept in CGT that provides a unique allocation. The nucleolus was introduced by Schmeidler (1969), and it follows a quasi-egalitarian theory of fairness to find the specific allocation of the grand coalition's worth that will minimize the dissatisfaction of the most dissatisfied coalition. One key assumption (and often critique) of the nucleolus is the anonymity of the various coalitions (Madani and Dinar, 2012). Effectively, the solution is determined using a "prepare for the worst" philosophy, in that, if no coalition will know their future, they will each try to maximize a benefit from the worst possible outcome. Taken from Ozyurt (2021b)'s analysis, it is given as the following:

$$N(G) = \{x \mid x \succ y \text{ for all payoff vectors } y\} \tag{3.3.11}$$

where both x and y are different possible payoff vectors, or distributions of the grand coalition. To find the nucleolus, a deficit value $d(S, x)$ is defined for each possible coalition S with respect to a payoff vector x. Deficits are calculated using equation 3.3.12.

$$d(S, x) = v\{S\} - \sum_{i \in S} x_i \tag{3.3.12}$$

Deficit vectors are calculated as a proxy value for dissatisfaction; therefore, a greater deficit value would amount to a greater dissatisfaction. Applying the payoff vector x, a cumulative folded deficit vector $d(x)$ with 2^n elements in said vector is created and, due to an anonymity assumption, is ordered from highest to lowest deficit values without consideration of coalition constituents or size.

$$d(x) = \left(d(S_i, x),\ d\left(S_j,\ x\right) \ldots d\left(S_{(2^n)},\ x\right)\right) for\ i\ \leq j \leq 2^n \tag{3.3.12}$$

$$d\left(S_j, x\right) \geq d(S_k, x) \text{ for } j \leq k \leq 2^n \tag{3.3.13}$$

Finally, we define a lexicographic ordering of all possible payoff vectors in the game, where a payoff vector x is better (or most preferable) than all other payoff vectors y if and only if there exists some index i between $1 \leq i \leq 2^n$ where the complaints remain the same up to index $i - 1$. Mathematically, this can be represented as

$$\begin{gathered} d\left(S_j, x\right) = d\left(S_j, y\right) \text{ for all indices } 1 \leq j < i \\ \text{and } d(S_i, x) < \ d(S_i, y) \end{gathered} \tag{3.3.14}$$

where $d\left(S_j, x\right)$ and similar variants are elements of the cumulative folded deficit vector. This solution concept has some key properties that make it ideal for an application in a coalitional setting. It will always lie in the Core (if the Core is not empty), and it will always exist in games where individual rationality is observed. It can also be thought of as an extension of the *least* Core. If the *least*-Core gives more than one approximation of an efficient allocation, the nucleolus essentially tries to satisfy the next highest dissatisfaction level of the coalitions (Benedek et al., 2020). The Nucleolus is useful for water conflicts, especially when used by an unbiased mediator to broker a solution. It is also useful in attempting to equalize benefit allocation, which is useful in conflicts where utility magnitudes vary significantly (Wu and Whittington, 2006).

3.4 STABILITY METRICS

While CGT solution concepts identify different allocation vectors as possible fair solutions for all players, differences in fairness interpretations along with a player's individual expectations on allocations, may undermine a strategy that mathematically may be acceptable by all. Individually, a player will always be most satisfied with a strategy that gives them the highest benefit from their expectations. The greater the distance from this expectation, the more likely they are to reject an associated strategy if the expectation value is less than the reference solution. In cooperative settings, however, the stability of a strategy would also need to account for multi-actor power dynamics. *Stability metrics* are therefore used as a measurement of resilience for a particular strategy. We can use stability metrics to find strategies where, for each player, their benefit from the particular strategy makes them unlikely to break an agreement by defecting to a strategic behavior. A set of diverse metrics to comprehensively assess stability from various avenues because the assessment of stability is more so a characterization of the strategy itself.

3.4.1 *EUCLIDEAN DISTANCE*

The Euclidean distance between two points is an approximate measurement of stability, commonly used in network design and other applications of algorithmic game theory (Friedemann et al., 2021; Berl et al. 1976). If there exist two allocation vectors a and b with Euclidean coordinates of $a = (a_i, a_j, a_k)$ and $b = (b_i, b_j, b_k)$, then the distance is the length of the line segment between each element of the respect points. Thus, the distance is calculated as

$$d = \sqrt{(a_i - b_i)^2 + \left(a_j - b_j\right)^2 + (a_k - b_k)^2} \tag{3.4.1}$$

Note, however, that each player's preference is to maximize their respective utilities. Thus, a possible allocation greater than a coalition's worth is perfectly acceptable, and an allocation's preference will continue to decrease as the magnitude of the difference between the coalition's worth and the reference solution. The distance will represent a value of total lost utility between all players, and a minimization of this value is preferred.

3.4.2 *LOEHMAN POWER INDEX*

The Loehman Power Index is an *ex-post* calculation developed by Loehman et al. (1979) based on a method suggested by Shapley and Shubik (1954) to measure the power of each player in a voting game. Essentially, the greater a player's power is, the more influence it can impose on the outcome of a game. Loehman et al. (1979)'s power index, extended for use to coalitional games, compares the gains of an individual with the total gains of the coalition, given as

$$\beta_i = \frac{x_i - v\{i\}}{\sum_{i \in N} (x_i - v\{i\})}, i \in N \tag{3.4.2}$$

$$\sum_{i \in N} \beta_i = 1$$

The power index is calculated for each possible allocation for each player. Ideally, a stable allocation is one where the power distribution is equitable across the players. Dominance from a particular player may dissuade other players to remain in the grand coalition. The Power Index has mainly been used in cost distribution games in common-pool resource allocations (Dinar and Howitt, 1997). The variation of power is given by a fairness index S_β, which is the standard deviation of the power indices (σ_β) divided by the mean value ($\bar{\beta}$). A greater value of S_β indicates a greater instability of a particular allocation.

$$S_\beta = \frac{\sigma_\beta}{\bar{\beta}} \tag{3.4.3}$$

3.4.3 PROPENSITY TO DISRUPT

The propensity to disrupt was first introduced by Gately (1974). It is defined as the ratio of the expected loss from all other players in a coalition if a player defects from a payoff allocation to the expected loss for the player. If we have a possible allocation $x = (x_i, x_j, x_k)$ for a 3-player coalitional game, then the propensity to disrupt for player i is given as

$$pd(i) = \frac{(x_j + x_k) - v\{j,k\}}{x_i - v\{i\}} \tag{3.4.4}$$

where $v\{j,k\}$ is the worth function of the sub-coalition with player $\{j,k\}$ and $v\{i\}$ is player i ‘s characteristic value. The propensity to disrupt can be either negative or positive, where greater magnitudes of positive propensity to disrupt values indicate that a higher threat by that player at disrupting the grand coalition. Thus, stable solutions can be characterized by low propensity to disrupt values, as this ensures a very low incentive (if at all) to defect (Gately, 1974). Alternatively, the higher the propensity to disrupt, the greater the leverage that a player in maintaining the grand coalition. Rankings are dependent on the average of each player’s propensity to disrupt for each allocation. The propensity to disrupt have also been used in cost allocations for utilities (Dinar and Howitt, 1997).

3.4.4 POLICY EFFICIENCY

The policy efficiency is a modification on the concepts of *price of anarchy* and *price of stability*. Both these concepts are used in traditional Nash Equilibrium games to estimate the efficiency of an equilibrium point. The *price of anarchy* measures the inefficiency of a system where multiple players have competing interests and little cooperation is observed. The *price of stability* instead finds the minimum “cost” that is needed for players to play at the optimal solution (Roughgarden et al., 2007). These concepts are used in this analysis to find the quality of our policy candidates. Both concepts, however, are used in instances of multiple equilibrium points within a strategic game.

$$eff = \frac{\sum_{i=1}^{N} x_i}{v\{N\}} \tag{3.4.5}$$

In our case, we treat each policy candidate as a potential equilibrium point. In the non-standardized Pareto-set, the policy candidate with the highest allocation sum (or the *optimal solution*) is equivalent to the grand coalition’s characteristic value $v\{N\}$. We can accordingly also calculate the *prices of anarchy and stability* for each individual player by finding the lowest efficiency, assuming the highest efficiency of 1 as a ratio implies a normalization of efficiency. By ranking efficiency, we can analyze stable policies as to whether they are maximizing utility capacities.

Table 3.1: A summary of the solution concepts and stability metrics used for this study.

Nucleolus	Asymmetric Nash-Harsanyi Solution	Symmetric Nash-Harsanyi Solution	Weighted Shapley Value	Symmetric Shapley Value
Attempts to find the imputation that **minimizes the dissatisfaction of the most dissatisfied player**. Application of Rawlsian social welfare function	Like symmetric solution, but with **differences in bargaining weights.** Similar fairness theory behind design and calculation of solution.	**An extension of the Nash bargaining solution as an *n*-player game.** Utilitarian design to determine allocations that will maximize product of differences between the player's characteristic values and allocations.	Allocations based on marginal contributions of each GC player **and probability weights based on coalitions perceptions of players.** Similar structure and assumptions as the sym. Shapley Value except for symmetry and efficiency.	Fair allocation solution based on the **marginal contributions of each grand coalition player** with equal likelihood of all coalitions. Index of the strength of a player in the grand coalition.
Assumptions: *anonymity of different coalitions, individual rationality* **Benefits:** uniqueness of solution, will always be in the Core (if Core exists), non-emptiness. **Limitations:** anonymity of different coalitions, little application to real CPR conflicts, potentially computationally expensive, nucleolus may require large deductions (ε) from each coalition and reduces policy efficiency, not guaranteed to be Pareto-efficient.	**Limitations:** all from symmetric solution but also requires knowledge on context-specific knowledge and regional relations to calculate bargaining weights.	**Assumptions:** *symmetry, individual rationality, invariance to transformations of original utility.* **Benefits:** large applicability in CPR conflicts, unique solution, consideration of all player's benefits, incorporates incomplete information and player rationality. **Limitations:** utilitarian design may be interfered with large utility magnitude differences, computational complexity, limited application to non-cooperative games.	**Benefits:** closer potential application to real-life conflicts, does not assume one collective thought amongst all players. **Limitations:** complexity in calculations, requirement of context-specific knowledge for probability weights, limited constraints, and small actual application.	**Assumptions:** *symmetry, efficiency, linearity* **Benefits**: attempted egalitarian distribution, uniqueness, independence from irrelevant outcomes **Limitations**: not necessarily in the Core, assumes rationality between players, excludes substitutes of interdependent utility.

Stability Metrics

Euclidean distance	Loehman Power Index	Propensity to Disrupt	Policy Efficiency
The physical distance between a ref. solution and a policy candidate. If ref. solution is larger, greater distances lead to lower preference of policy candidate.	A nation's gain from their characteristic function for an allocation relative to the sum of all gains from others. Larger power indices mean inequal benefits.	Ratio of expected loss for all other players in a GC when a nation defects versus the loss to the nation itself. A measure of a nation's leverage in a negotiation.	A measure of how large a policy's total utility is compared to the maximum possible utility possible within the Pareto set.

4. EXPERIMENTAL SETUP

After the research on various CGT solution concepts and stability metrics was concluded, insights were compiled to form a plan for the stability analysis, as detailed in Figure 4.1. To develop a method that can be applied in various situations, we chose to create and analyze results from combinations of stability metrics and solution concepts. The workflow was developed based on prior stability analyses and applications of CGT solution concepts (Dinar and Nigatu, 2013; Wu and Whittington, 2006; Dinar and Howitt, 1997). Once objective values were obtained, they were converted into a utility function, allowing for easy comparison of the allocation to each country. The game can be partially considered a cost-sharing game, where the cost to each nation is the lost opportunity cost from a maximum utility attainment.

In the ENB, volumetric constraints and uses of the Nile river mean that a gain for one player's objectives will require a sacrifice on the part of other players. An optimal solution will inevitably require a compromise from (or a cost to) all nations. By assuming transferable utilities (TU), the aim of the conflict is expanded from attaining a maximum payoff for an individual player to maximizing the payoffs of the coalition, as side-payments or compensations would theoretically be possible between nations in instances of a sacrifice by one nation. By extension, this would entail forming the coalition with the highest possible worth. Treating cost-sharing games as TU games has been successfully applied in a variety of fields, including urban water supply and transmissions in power systems (Young et al., 1982; Contreras, 1997).

Following conversions to a common utility unit, characteristic function values can be determined based on what is the expected utility for a particular coalition. CGT solution concepts will each find unique allocations with an underlying theory of fairness; as such, there is a strong possibility that each nation will consider a different solution as fair. By analyzing the stability across a variety of solution concepts, we address these differences in opinion to see how allocations change with a solution concept and, by extension, how their preference amongst the players alters as a result.

The *ENO* model was run to obtain a Pareto-set of optimized objectives. Similar to Sari (2022), the model was connected to the Exploratory Modelling and Analysis (EMA) Workbench and used a ε-NSGA II evolutionary algorithm for its optimization (Kwakkel, 2017). The model was run using the DelftBlue High Performance Computing Center at the Delft University of Technology.

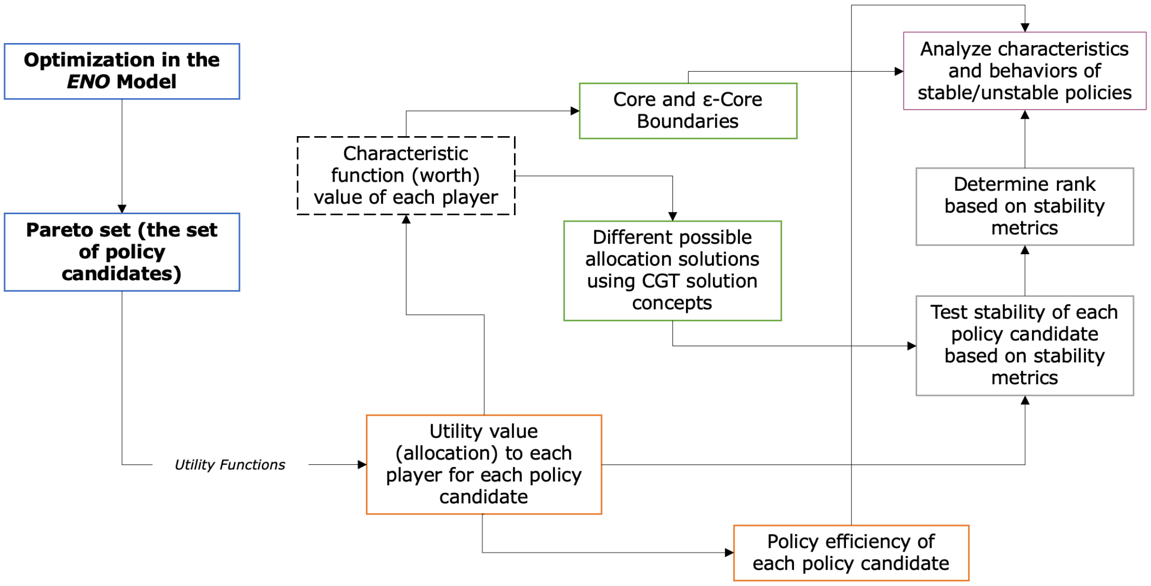


Figure 4.1: A diagram of the experimental setup for this stability analysis.

4.1 UTILITY CALCULATIONS

In keeping with the transferable utility assumption, only monetary utility or physical water allocations are feasible for regional policymakers. However, Dinar and Nigatu (2015) have highlighted the significant transactional costs associated with water market management, assuming that the required infrastructure is already in place. Therefore, we have chosen to use monetary utility, specifically the total annual income in United States dollars (USD). It should be noted that in all utility equations, the term *INC* refers to the income (or utility generated) from a specific objective.

1. **Egypt:** Egypt's objectives, as discussed in Section 3.2, require minimization for optimization. However, the goal of a player is still to maximize their payoffs unless the game is strictly a cost-sharing game. To determine the maximum potential value for both objectives, a deductive approach was used by subtracting the objective values from the maximum possible allocation value. For Egypt's irrigation deficit a maximum allocation value of 55.5 BCM per year - Egypt's annual allocation from the 1959 Nile Water Agreement - was used as a reference and assumed to be fully utilized for agricultural purposes. Deducting the deficit value flips the direction of preference, where a smaller deficit results in a higher income from agriculture. Similarly, for the HAD low-water level frequency, the objective values represent decimal percentages. The maximum possible value is achieved when this frequency is zero, meaning that HAD always has sufficient water height for hydropower production. Egypt's final utility value for each policy is then obtained by adding the income from both sources (Equation 4.1.3).

$$INC_{HAD} = DF_{3\%} * (1-\alpha)(BAHP_{HAD})(C_{HP}) \qquad (4.1.1)$$

$$DF_{3\%} = \frac{1}{(1+\delta)^t}$$

where α is the ratio of time when the HAD is below minimum power generation level (a direct input from the optimization results), $BAHP$ is a base annual hydropower production level of the HAD, C_{HP} is an average cost of selling hydropower, and $DF_{3\%}$ is a discount rate using a social discount factor (δ) of 3 percent (Horsch et al., 2022). Exact parameter values are found in Appendices A.[1, 3, 5, 7, 9].

$$\sum INC_{Egp.\ Irr} = \frac{\zeta_i}{55.5 + DEF} * DF_{3\%} * \sum_{i \in C_{Egypt}} \left(\frac{\zeta_i * Y_i * P_i}{WU_i} \right) \tag{4.1.2}$$

where C_{Egypt} is a set of crops that make up the majority of Egypt's agricultural income (USDA Foreign Agriculture Service, 2022). ζ_i is the amount of allocated water to a crop after the deficit's deduction from 55.5 BCM per year. Y_i is a crop's annual yield, WU_i is the water use for a crop, and P_i is the average selling price of a crop (United Nations, 2022). DF is a discount rate using a social discount factor (δ) of 3 percent. DEF is Egypt's deficit amount (in BCM per year). Exact parameter values are found in Appendix A.11. Finally, to assign one total utility value to Egypt, we simply add incomes generated from HAD hydropower production and the agriculture through a partial deficit. This will give us the "total utility" (TU) for Egypt. Egypt is the only nation that requires an addition of individual utilities.

$$TU_{Egp} = \left(INC_{HAD} + \sum INC_{Egp.\ Irr\ Costs} \right) \tag{4.1.3}$$

2. **Sudan:** Sudan's only relevant objective is similar to Egypt's irrigation deficit objective, where a direction of minimization is preferred. The only difference is the maximum potential value, which uses the value of 18.5 BCM per year (Sudan's allocated amount in the 1959 Nile Water Agreement).

$$\sum INC_{Sudan.\ Irr} = \frac{\zeta_k}{18.5 + DEF_{Sud}} * DF_{3\%} * \sum_{k \in C_{Sudan}} \left(\frac{\zeta_k * Y_k * P_k}{WU_k} \right) \tag{4.1.4}$$

where C_{Sudan} is a set of crops that make up the majority of Sudan's agricultural income (USDA Foreign Agriculture Service, 2022). ζ_k is the amount of allocated water to a crop *k* after the deficit's deduction from 18.5 BCM per year. Y_k is a crop *k's* annual yield, WU_k is the water use for a crop, and P_k is the average selling price of a crop (United Nations, 2022). DEF_{Sud} is Sudan's deficit amount (in BCM per year). DF is a discount rate using a social discount factor (δ) of 3 percent. Exact parameter values are found in Appendix A.[2, 4, 6, 8, 10].

3. **Ethiopia**: Unlike objectives for Egypt and Sudan, Ethiopia's only objective is the annual amount of hydropower generation from the GERD, which it obviously seeks to maximize. Therefore, the income from the GERD's hydropower production is given as:

$$INC_{GERD} = DF_{3\%} * \sum_{j \in U} \beta_j * P_{HP} \tag{4.1.5}$$

where U is the set of potential users (either domestic or foreign). For each user j, β_j is the amount of hydropower that is allotted to that user (using a direct input from optimization results), P_{HP} is the associated selling price of electricity, and DF is a discount rate using a social discount factor (δ) of 3 percent. Exact parameter values are found in Appendix A.12.

One important difference in the utility function formulation, as compared to other studies, is our choice to use a constant utility progression rather than a *diminishing* marginal utility. With diminishing marginal utility, a product's utility will decrease as the consumption increases. Alternatively, this also means, as availability of the product increases, that consumers are willing to spend less to obtain said product due a decrease in subjective value (Greene and Baron, 2001). For the purposes of this analysis, a diminishing marginal utility would likely not be relevant. This is for methodological and conceptual reasons.

The utility measurements are done with the intention of being ordinal rather than cardinal as we are identifying the most and least stable policies (in addition to understanding stable policy behavior) in the Pareto set. Therefore, they should not be assumed to be precise values. As noted earlier, utilities for this analysis are assumed to be *Neumann-Morgenstern* utilities, commonly used when performing decision-making under risk or uncertainty (Greene and Baron, 2001). By definition, this means that each player's bounded rationality will make them want to maximize the expected utility that they can receive. In the ENB's case, all nations are looking for large-scale economic growth. Ethiopia's and Egypt's targets of GERD and HAD hydropower production, respectively, mean that higher water volumes would generate higher revenue. Similarly, for consumptive purposes for Egypt and Sudan, irrigation deficits need to be reduced as much as possible, and higher volumes of water allow for nations to fulfill closer to this demand. The objectives highlight that energy production is a direct competitor to consumptive uses like agriculture and human demand (Kucukmehmetoglu, 2009).

However, benefit from a utility is in reality a subjective value. Giocoli (1998)'s analysis on Bernoulli's 1738 introduction of marginal utility shows that the utility of a player's gain, instead of the actual monetary utility itself, is what is pertinent to a rational player's decision. Water scarcity will affect the subjective value that is placed on water (Zetland, 2021). Despite there being an overall scarcity of water in the ENB, each nation's individual scarcity can also be exacerbated or mitigated based on the choice of allocation. All nations recognize that smaller expected future volumes mean that accumulation of water is necessary. In short, there is little information on the gradient of decreasing subjective value per nation with each volumetric unit of water. The analysis's epistemic bounds mean that the only indication of a gain from utility is through comparison with a nation's characteristic value. This is also one of the reasons why the Euclidean distance stability metric was incorporated. Lastly, our analysis also uses monetary utility and a transferable utility assumption; this type of utility's worth would not decrease in this context, regardless of who is in possession.

We chose to standardize the total utility value of each policy candidate so that each was equivalent to the grand coalition's characteristic value. This decision was made because policy candidates originally showed different total utility values. As we are attempting to rank relative policy stability based on metric values, using the normal set for calculations opened the possibility of Type I and II errors. In other words, a policy candidate's ranking may fail to reflect its actual stability simply due to a greater magnitude of difference. Also, standardization allows for the efficiency condition In CGT solution concepts (Shapley, 1971) to be fulfilled. Original weights of each nation's allocations were retained in the standardization process.

4.2 SENSITIVITY ANALYSIS OF UTILITY FUNCTIONS

In order to test the efficacy of the chosen parameter values for this analysis, a sensitivity analysis was conducted. Upon a review of literature, there were not any studies found that specifically performed a sensitivity analysis on utility functions. However, for the purposes of the stability analysis, our primary objective is to understand the relationships between input and outputs of the utility function. Furthermore, through this we are able to determine potential ranges of parameters that may inflate a nation's determined utility. Due to the utility functions' complexity (mainly through potential overparameterization), multivariate sensitivity analysis would have been ideal to obtain the highest insight levels possible and test function robustness (Sterman, 2000; van Griensven et al., 2006). However, we suffer from a *curse of dimensionality* for Egypt and Sudan's utility functions for irrigation demand deficit values, meaning that testing each parameter against a variation of all others would have been computationally infeasible due to the sheer number of possible combinations. Therefore, this issue for these utility functions was approached in two manners.

First, parameter variations were compared within the same parameter category *(cost, yield, area, or water use)* whenever applicable. This was the most feasible option, as just picking univariate sensitivity analysis could have misdirected robustness conclusions due to the utility function's nonlinear structure (Saltelli et al., 2019). Second, to get a comprehensive view of the existing relationship when changes between two variables occurred, we chose to perform a sampling of variation points with low discrepancy sequences. To do this, an initial screening of different parameters is used to find parameters that did not cause large changes in utility values. Once this was found, a smaller percent variation was enacted on those to fully see their effect. After this, equally spaced sample values were taken in the variation range. This method had been used previously to help with high-dimensionality cases. While other methods (such as Sobol indices) could have been used to determine variance-based sensitivity metrics, these were deemed to not be necessary due to the relatively simple purpose for our sensitivity analysis.

SENSITIVITY ANALYSIS INSIGHTS

Tables 4.1.1 to 4.1.4 show heatmaps detailing the results of the sensitivity analysis. Appendix C shows extensive hexagonal bin plots from the analysis and Appendix C.11 for a table on full value changes for each parameter. The Python-based *sensitivity* package was used for this portion. Note that the utility values generated here are non-standardized, meaning that they are direct calculations from the objectives in each policy candidate. After an initial screening, Egypt's yield parameters showed relatively small effects on the utility when we performed a 30 percent variation on them. Therefore, we reduced the spread of this category to within 20 percent, which led to a much more descriptive set of results.

There are a few notable observations in Table Set 4.1.4. As expected, variations in the irrigation deficit value for Egypt (and, as seen later, Sudan) created the highest range of utility value differences. Mathematically, this would make sense as this deficit value will have an impact on each parameter in the function, so higher deficit values will create a joint reduction in monetary output from agriculture.

Most crops did not show large changes in the utility. Most combinations in the variations between these parameters amounted to a utility difference of roughly USD 0.1 – 0.2 billion per year. However, wheat, rice, and corn were the crops that produced the greatest range of utility values.

Wheat's variations in the parameter categories were consistently producing high ranges. Given the high value of wheat's area in Egypt combined with its relatively high yield and cost of sale, a low water use requirement also inflates this number. Wheat, thus, is a fairly efficient crop in Egypt, and its associated parameters expose large sensitivity from the utility function. Large changes with rice's parameters mainly emerged in water usage, area, and yield categories (although less so in the latter than the two former categories). The rice crop has the highest yield of the crop set, along with relatively high areas and water usage requirements. However, its cost is among the lowest, which is most likely why a greater dominance (in terms of range of utility) from the other two major crops in the cost category. Finally, corn's low and high utility values have regularly large differences. Corn has the second largest area after wheat as well as high yield and cost of sale values. When we see that water usage is also quite low, corn seemingly follows a similar impact behavior as what was seen with wheat.

Table 4.1.3 showed expected results for HAD parameters. This function shows linear behavior and is mainly dependent on frequency. As frequency decreases, an accompanying increase in the base hydropower production amount would exponentially increase HAD utility. Of course, this is infeasible given the great dependence that the Egyptian economy has on agriculture (Basheer et al., 2018). In Table 4.1.1, the hydropower production amount of the GERD obviously has a significant impact on the utility behavior and functions in a similar role as does the irrigation deficit values for Egypt and Sudan. Otherwise, the largest sensitivity is seen through changes in interactions between the cost for exporting hydropower against two other parameters: the percentage of domestic hydropower and, by extension, the percentage of exported hydropower. Interestingly, the gradients of utility changes are relatively steeper when comparing export prices with production quantity as compared to domestic prices with production quantity. Logically, this indicates a greater desire to maximize production to export more electricity, as it has already started doing with neighboring Kenya and Sudan (Basheer et al., 2021). It should be noted, however, that many of the interactions produced relatively large utility ranges, meaning that Ethiopia's hydropower utility function can be quite sensitive to changing values.

Finally, when we look at variations in Sudan's parameters, Tables 4.1.2 (a) through (d) show that the greatest utility differences occur with the sorghum parameters. This can be explained by sorghum's area being twice the amount of the next crop in order (groundnuts). The sorghum area parameter has its largest impact when it maintains a large relative area than other crops. Otherwise, most other parameters interactions produce lowest and highest values that are within the range set by the sorghum parameters. In short, Sudan's utility function is quite more confined in its utility movements as compared to its analog function with Egypt. This makes one important observation. Changes in parameter values will have a larger impact on Egypt's irrigation deficit utility than any others. Therefore, to look at more equitable allocation strategies, it would be best to limit the "runaway" behavior of Egypt's utility.

Table 4.1.1: Low and high values for the income generated through parameter variations in Ethiopia's GERD income utility function. These are based on the HAD low-water level frequency objective. **Terminology:** "cost_export" = cost of sale for exporting hydropower (USD per kWh); "cost_dom" = cost of sale for domestic hydropower use (USD per kWh); "percent_export" = % of hydropower exported; "percent_dom" = % of hydropower used domestically; "prod_value" = the GERD's production amount of hydropower (TWh per year) (objective value). All values are presented in [USD billion per year] using non-standardized Pareto-set policy objective values.

	cost_ dom (low)	cost_ dom (high)	percent_ export (low)	percent_ export (high)	percent_ dom (low)	percent_ dom (high)	prod_ value (low)	prod_ value (high)
cost_ export	0.009	0.203	0.046	0.221	0.020	0.190	0.040	0.188
cost_ dom			0.039	0.172	0.062	0.191	0.057	0.165
percent_ export					0.052	0.159	0.066	0.152
percent_ dom							0.069	0.150

Table 4.1.2a: Low and high values for the income generated through parameter variations for crop yield in Sudan's irrigation income utility function. The parameter variations, **from top to bottom**, are for **(a) crop yield "Y"** (kg per square meter)**, (b) crop area "Area"** (square meter)**, (c) crop water usage "WU"** (cubic meters per square meter), and **(d) cost of sale "cost"** (USD per kg)**.** These are based on the irrigation demand deficit objective. All parameter values were altered for all crops denoted in C_{Sudan}. **Terminology:** "cot" = cotton; "gn" = groundnuts; "wh" = wheat; "sg" = sorghum; "sudan_def_value" = the deficit value that Sudan experiences through a policy (objective value). All values are presented in [USD billion per year] using non-standardized Pareto-set policy objective values.

	Y_gn (low)	Y_gn (high)	Y_wh (low)	Y_wh (high)	Y_sg (low)	Y_sg (high)	sudan_ def value (low)	sudan_ def value (high)
Y_cot	0.338	0.414	0.360	0.392	0.312	0.436	0.300	0.461
Y_gn			0.327	0.426	0.279	0.470	0.273	0.502
Y_wh					0.301	0.448	0.291	0.475
Y_sg							0.252	0.529

	Area_ gn (low)	Area_ gn (high)	Area_ wh (low)	Area_ wh (high)	Area_sg (low)	Area_sg (high)	sudan_ def value (low)	sudan_ def value (high)
Area_cot	0.379	0.381	0.369	0.391	0.369	0.395	0.305	0.463
Area_gn			0.368	0.390	0.368	0.395	0.304	0.464
Area_wh					0.361	0.407	0.297	0.475
Area_sg							0.296	0.480

	WU_gn (low)	WU_gn (high)	WU_w h (low)	WU_wh (high)	WU_sg (low)	WU_sg (high)	sudan_ def value (low)	sudan_ def value (high)
WU_cot	0.362	0.435	0.393	0.399	0.322	0.490	0.317	0.485
WU_gn			0.362	0.434	0.301	0.541	0.291	0.527
WU_wh					0.322	0.489	0.317	0.484
WU_sg							0.259	0.593

	cost_gn (low)	cost_gn (high)	cost_wh (low)	Cost_w h (high)	cost_ sg (low)	cost_ sg (high)	sudan_ def value (low)	sudan_ def value (high)
cost_cot	0.349	0.433	0.376	0.406	0.319	0.465	0.312	0.479
cost_gn			0.338	0.444	0.280	0.503	0.282	0.525
cost_wh					0.308	0.476	0.304	0.492
cost_sg							0.257	0.564

Table 4.1.3: Low and high values for the income generated through parameter variations in Egypt's HAD utility function. These are based on the HAD low-water level frequency objective. **Terminology**: "HAD low frequency" = frequency value of the HAD below power generation levels (objective value); "base_annual_production" = the baseline annual production value of the HAD (kWh); "cost_hp" = the cost of sale of hydropower (USD per kWh). All values are presented in [USD billion per year] using non-standardized Pareto-set policy objective values.

	base_annual production (low)	base_annual production (high)	cost_hp (low)	cost_hp (high)
Freq. HAD low-water level	0.000	1.750	0.000	2.200
Base_annual production			0.200	1.400

Table 4.1.4: Low and high values for the income generated through parameter variations in Egypt's irrigation income utility function. The parameter variations, **from top to bottom**, are for **(a) crop yield "Y"** (kg per square meter)**, (b) crop area "Area"** (square meter), **(c) crop water usage "WU"** (cubic meters per square meter), and **(d) cost of sale "cost"** (USD per kg)**.** These are based on the Egypt irrigation demand deficit objective. **Terminology**: All parameter category abbreviations are the same as in Tables 4.2.2(a-d). "barley" = barley; "corn" = corn; "cot" = cotton; "gn" = groundnuts; "sb" = soybeans; "sg" = sorghum; "wh" = wheat; "rice" = rice; "egypt_def value" = irrigation deficit value that Egypt experiences through a policy (objective value). All values are presented in [USD billion per year] using non-standardized Pareto-set policy objective values.

	Y_corn (low)	Y_corn (high)	Y_cot (low)	Y_cot (high)	Y_gn (low)	Y_gn (high)	Y_sb (low)	Y_sb (high)	Y_sg (low)	Y_sg (high)	Y_wh (low)	Y_wh (high)	Y_rice (low)	Y_rice (high)	egypt_def value (low)	egypt_def value (high)
Y_barley	3.205	3.631	3.412	3.423	3.34	3.495	3.414	3.422	3.408	3.428	3.120	3.716	3.324	3.511	1.749	5.652
Y_corn			3.205	3.630	3.133	3.702	3.207	3.629	3.201	3.635	2.913	3.923	3.117	3.718	1.855	5.309
Y_cot					3.341	3.495	3.415	3.421	3.408	3.427	3.120	3.715	3.325	3.511	1.746	5.653
Y_gn							3.342	3.493	3.336	3.500	3.048	3.787	3.252	3.583	1.709	5.781
Y_sb									3.410	3.426	3.122	3.714	3.326	3.509	1.747	5.658
Y_sg											3.116	3.720	3.320	3.515	1.743	5.669
Y_wh													3.032	3.803	1.597	6.145
Y_rice															1.701	5.807

	Area_ corn (low)	Area_ corn (high)	Area_ cot (low)	Area_ cot (high)	Area_ gn (low)	Area_ gn (high)	Area_ sb (low)	Area_ sb (high)	Area_ sg (low)	Area_ sg (high)	Area_ wh (low)	Area_ wh (high)	Area_ rice (low)	Area_ rice (high)	egypt_ def value (low)	egypt_ def value (high)
Area_barley	3.286	3.393	3.286	3.401	3.240	3.445	3.327	3.358	3.293	3.394	3.214	3.460	3.189	3.512	1.702	5.554
Area_corn			3.252	3.422	3.201	3.462	3.297	3.383	3.260	3.416	3.169	3.474	3.148	3.525	1.687	5.597
Area_cot					3.209	3.477	3.296	3.390	3.262	3.426	3.180	3.490	3.162	3.549	1.686	5.607
Area_gn							3.250	3.434	3.217	3.471	3.128	3.528	3.118	3.594	1.663	5.680
Area_sb									3.303	3.383	3.225	3.445	3.198	3.500	1.708	5.536
Area_sg											3.189	3.483	3.169	3.541	1.690	5.595
Area_wh													3.083	3.597	1.650	5.705
Area_rice															1.636	5.789

	WU_ corn (low)	WU_ corn (high)	WU_ cot (low)	WU_ cot (high)	WU_ gn (low)	WU_ gn (high)	WU_ sb (low)	WU_sb (high)	WU_sg (low)	WU_sg (high)	WU_wh (high)	WU_wh (high)	WU_rice (low)	WU_rice (high)	egypt_def value (low)	egypt_def value (high)
WU_barley	3.045	3.678	3.286	3.409	3.309	3.386	3.329	3.365	3.278	3.418	3.024	3.708	3.042	3.686	1.704	5.565
WU_corn			3.020	3.716	3.039	3.688	3.055	3.664	3.013	3.726	2.798	4.071	2.814	4.044	1.563	6.058
WU_cot					3.278	3.418	3.298	3.397	3.248	3.454	3.000	3.747	3.016	3.724	1.688	5.617
WU_gn							3.321	3.374	3.270	3.426	3.017	3.718	3.035	3.695	1.699	5.578
WU_sb									3.289	3.405	3.033	3.694	3.052	3.671	1.706	5.545
WU_sg											2.992	3.757	3.010	3.734	1.683	5.631
WU_wh													2.796	4.080	1.552	6.108
WU_rice															1.562	6.071

	cost_ corn (low)	cost_ corn (high)	cost_ cot (low)	cost_ cot (high)	cost_ gn (low)	cost_ gn (high)	cost_ sb (low)	cost_ sb (high)	cost_ sg (low)	cost_ sg (high)	cost_ wh (low)	cost_ wh (high)	cost_ rice (low)	cost_ rice (high)	egypt_def value (low)	egypt_def value (high)
cost_barley	3.069	3.858	3.458	3.469	3.36	3.567	3.459	3.468	3.444	3.484	2.994	3.849	3.288	3.608	1.769	5.738
cost_corn			3.070	3.857	2.972	3.955	3.071	3.857	3.056	3.872	2.605	4.237	2.900	3.996	1.570	6.381
cost_cot					3.361	3.566	3.460	3.468	3.445	3.483	2.994	3.848	3.289	3.607	1.770	5.737
cost_gn							3.362	3.565	3.348	3.581	2.897	3.946	3.192	3.704	1.720	5.898
cost_sb									3.446	3.482	2.995	3.847	3.290	3.606	1.770	5.736
cost_sg											2.981	3.279	3.275	3.622	1.763	5.761
cost_wh													2.824	3.987	1.532	6.366
cost_rice															1.683	5.966

4.3 CHARACTERISTIC VALUES

Characteristic values will form the basis of the following stability analysis. Shapley and Shubik (1973) discuss how there are various ways of determining the characteristic worth of a coalition, depending on the context and associated strategies of a game. Regardless, the characteristic function values indicate what that a player can expect to receive. In our case, the stability of a policy is being determined relative to other candidates in the optimized set; therefore, simply designating the maximum possible value of each nation's utilities would inevitably lead to a small number of policies being accepted by individual nations just because of their expected allocation amount. Instead, to find the characteristic value of each nation, probability density functions were used to distribute a nation's outcomes across all policies. The value associated with the highest density is that which occurs most often; this is accepted to be the utility value that a nation can expect with the highest probability.

There are limitations to this approach. While there exist different methods for calculating characteristic values, several are incompatible in this analysis. Many of these approaches require information on coalition probabilities or external information from regional authorities, which was not feasible (Gromova and Petrosyan, 2017). Second, this inherently means that we do not deem a coalition's worth by the absolute best they can achieve. However, since each policy candidate effectively acts as instructions for long-term water management, choosing the most probable solution would be a feasible amount as a nation's worth. For the characteristic values of sub-coalitions and the grand coalition, the superadditivity condition was followed, shown below for two players $i \text{ and } j$:

$$v\{i \cup j\} \geq v\{i\} + v\{j\} - v\{i \cap j\} \tag{4.3.1}$$

No value intersections are assumed in this game, meaning that economic co-dependencies or production linkages are not considered. For each coalition, individual utility values of the relevant nations were added, and the highest possible value that satisfied the above condition was chosen. This is in accordance with traditional coalitional game theory practice.

For multi-player coalitions, we must assume that the policy that has the greatest overall utility is the optimal candidate that encouraged cooperative strategies. Following this, policies with the smallest total utility are those that allowed anarchy, or an incomplete cooperative strategy among different players. This assumption, recall, was discussed when introducing policy efficiency. This does not necessarily imply that each player's utility would be maximized when the overall utility is maximized; the nature of this conflict guarantees that atleast one player will experience a loss to another's benefit. Therefore, we simply look for the largest characteristic value knowing that a transferable utility assumption would allow for compensations to occur after a policy is chosen.

Table 4.2: Calculated characteristic values for each possible coalition in the game. Recall that these were calculated after converting objectives to utility values.

Notation	Coalition Members	Value [USD billion /year]
$\boldsymbol{v}\{\emptyset\}$	Null	0
$\boldsymbol{v}\{\boldsymbol{E}\}$	Egypt	5.1257
$\boldsymbol{v}\{\boldsymbol{S}\}$	Sudan	0.4609
$\boldsymbol{v}\{\boldsymbol{Et}\}$	Ethiopia	0.4632
$\boldsymbol{v}\{\boldsymbol{E}-\boldsymbol{S}\}$	Egypt, Sudan	6.3441
$\boldsymbol{v}\{\boldsymbol{E}-\boldsymbol{Et}\}$	Egypt, Ethiopia	6.2238
$\boldsymbol{v}\{\boldsymbol{S}-\boldsymbol{Et}\}$	Sudan, Ethiopia	0.9259
$\boldsymbol{v}\{\boldsymbol{N}\}$	Egypt, Sudan, Ethiopia	6.6819

5. RESULTS

In Section 5, we present the results from the stability analysis. Most calculations and visualizations for the analysis were conducted using Python. Nash-Harsanyi solutions were solved using a *Wolfram Mathematica*-based program as its solution algorithm is better equipped for linear programming problems. The nucleolus and any further inspection of individual parameters were done using Microsoft Excel. This section is constructed to contribute to research question (b)'s answer. To determine the solution space of acceptable allocations, the Core is found and presented first. Next, the baseline analysis and the CGT solution concepts are presented along with important observations. In-depth explanation of important phenomena is then discussed in Section 6.

5.1 THE CORE AND ε -CORE

Calculations for the Core and ε -Core are located in Appendices E.1 and E.2, respectively. Solving the system of linear inequalities to satisfy the Core's conditions led to a mathematical contradiction. This meant that this particular game's Core is empty, and that no truly stable solution existed for this particular game without accounting for individual nations' incentives to deviate. Therefore, bounds for the ε -Core were calculated to find confines for near-stable allocations. As the value of ε increases, more policies are deemed acceptable due to a broadening of the area of the acceptable solution space, as shown in Figure 5.1 through the highlighted trapezoids. For each solution, an ε value can be calculated as the highest deduction necessary for the policy to be acceptable to all nations. However, recall that the ε value is effectively a deduction from characteristic values, meaning that lower ε values are preferred to keep total utility in the grand coalition as efficient as possible.

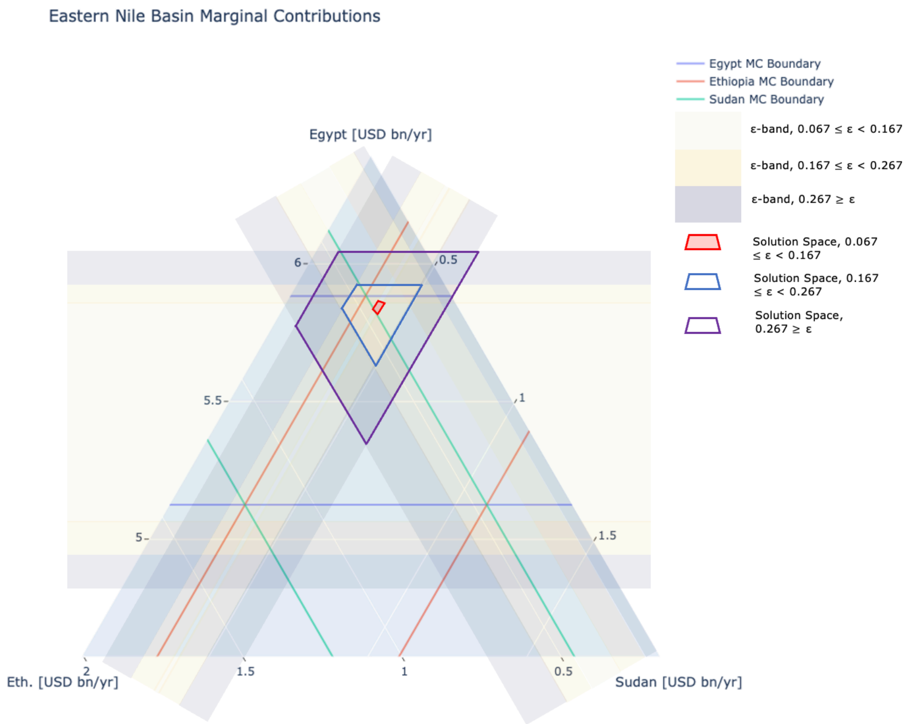


Figure 5.1: Marginal contributions (MC) of each ENB nation. Epsilon-core ranges for all three nations are overlaid. As the value of *epsilon* (in units of USD billion per year) increases, it results in a broadened solution space of near-non dominated allocations (where the Core would have had absolutely non-dominated solutions). Broadenings are seen by expanding trapezoids. Boundary values are found in Appendix E.3.

5.2 ALLOCATIONS FOR ALL SOLUTION CONCEPTS

Table 5.1: A table showing the allocations to each ENB nation from various CGT solution concepts. The baseline analysis used individual nation's characteristic values as the solution.

Solution Concept	**Egyptian Allocation [USD billion per year]**	**Sudanese Allocation [USD billion per year]**	**Ethiopian Allocation [USD billion per year]**	**Required *Epsilon* value [USD billion per year]**
Baseline Analysis	5.1257	0.4609	0.4632	0.126
Symmetric Shapley Value	5.5679	0.5865	0.5275	0.190
Egypt and Sudan vs. Ethiopia (PF1)	5.7189	0.9913	0.4510	0.537
Full Coalition in the ENB (PF2)	5.6553	0.7264	0.3884	0.269
Egypt vs. Sudan and Ethiopia (PF3)	5.4096	0.5379	0.4394	0.102
Symmetric Nash-Harsanyi Solution	5.3364	0.6716	0.6738	0.336
Nucleolus	5.8187	0.4627	0.4005	0.067

Table 5.1 shows the various allocations determined through each main solution concept. For the baseline analysis, we assume the stable solution to be individual characteristic values. This is because these solutions theoretically would be the minimum acceptable values for each nation. Note that each problem formulation refers to a weighted Shapley Value calculation, where probability weights for each coalition are not treated equally as in the symmetric Shapley Value and differ based on geopolitical context. Of all, only the symmetric solution concepts and the nucleolus fulfill the efficiency constraint. Weighted Shapley Values are not subject to this constraint, and differences in coalition probability weights between nations may indicate more difficult negotiations when using these as potential reference solutions.

Egypt's allocations exhibit the highest degree of dispersion while Ethiopia's allocations exhibit the lowest degree. Sudan's allocations also show a similar level of dispersion, with the only exception being in Problem Formulation 1 when it enters an alliance with Egypt. The symmetric Shapley Value's egalitarian fairness approach to an allocation, in this case, is thwarted by the large characteristic value for Egypt, which is why we still see relatively high allocations to Egypt under this solution concept. Alternatively, the utilitarian fairness approach for the symmetric Nash-Harsanyi solution meant that it optimized the group's total value by maximizing the product of each nation's benefit from their characteristic value. This may account for the higher allocations for Ethiopia and Sudan compared to other solution concepts, which may not have given as much weight to their contributions.

The required ε values also indicate the feasibility of different solution concepts. Recall that smaller ε values are preferred to maintain high total policy efficiency. These were calculated by finding the minimum ε value with which a solution concept's allocation is within all expanded marginal contribution bounds. Most solutions require relatively small deductions to be acceptable. The asymmetric Shapley Value requires the largest ε value for this solution to be acceptable by all player's imputations. This is mostly attributed to Sudan's abnormally large allocation. This deduction would incur great damage on expected utility for all nations and thus would not be realistic. The symmetric Nash-Harsanyi's solution has a large ε value due to Ethiopia's relatively slim margins for acceptable allocations. Because it rewards Ethiopia with a large amount, it also requires larger deductions from other nations, which can also infringe on this solution's feasibility.

5.3 BASELINE ANALYSIS

A Pareto set of 557 different policies emerged from the baseline optimization. Figure 5.2 shows the various policy candidates and the trade-offs experienced; several policies are highlighted that are shown to either optimize a specific objective or are compromise policies. Recall that Egypt and Sudan's 90th percentile irrigation deficit objectives, while present in the model, are both not used for the analysis past the optimization stage and thus not shown. For Sudan's annual irrigation deficit and Egypt's HAD low-water level frequency objective, while only showing one optimizing policy here for each, actually had many instances of an optimal policy (where zero deficit or frequency, respectively, was observed). Furthermore, in accordance with Sari (2022)'s workflow, we found compromise policies, based on a minimum percentile achievement for all objectives (*Percentile Threshold,* policy 106) and an absolute value albeit normalized threshold (*Absolute Threshold,* policy 329). For this specific Pareto set, a policy candidate where each objective attained a minimum normalized absolute value of 0.76 (assuming an optimum value of 1) was found. For the *Percentile Threshold* policy, the 48th percentile was the lowest percentile value where each objective achieved an acceptable value in a policy candidate.

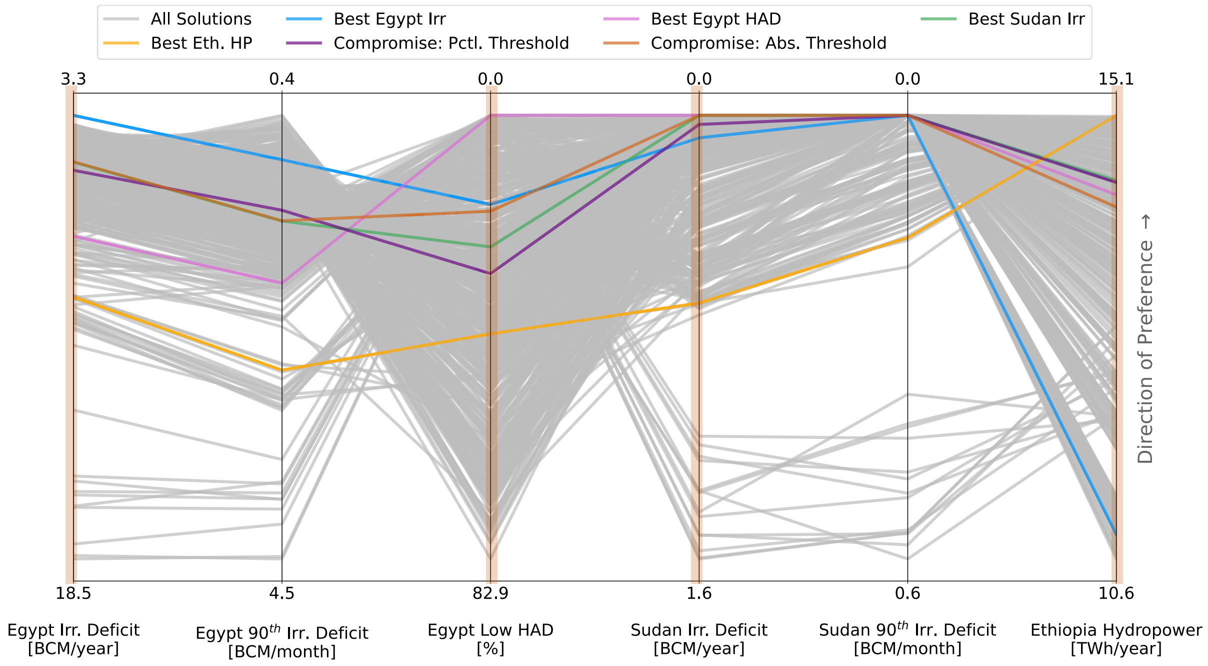


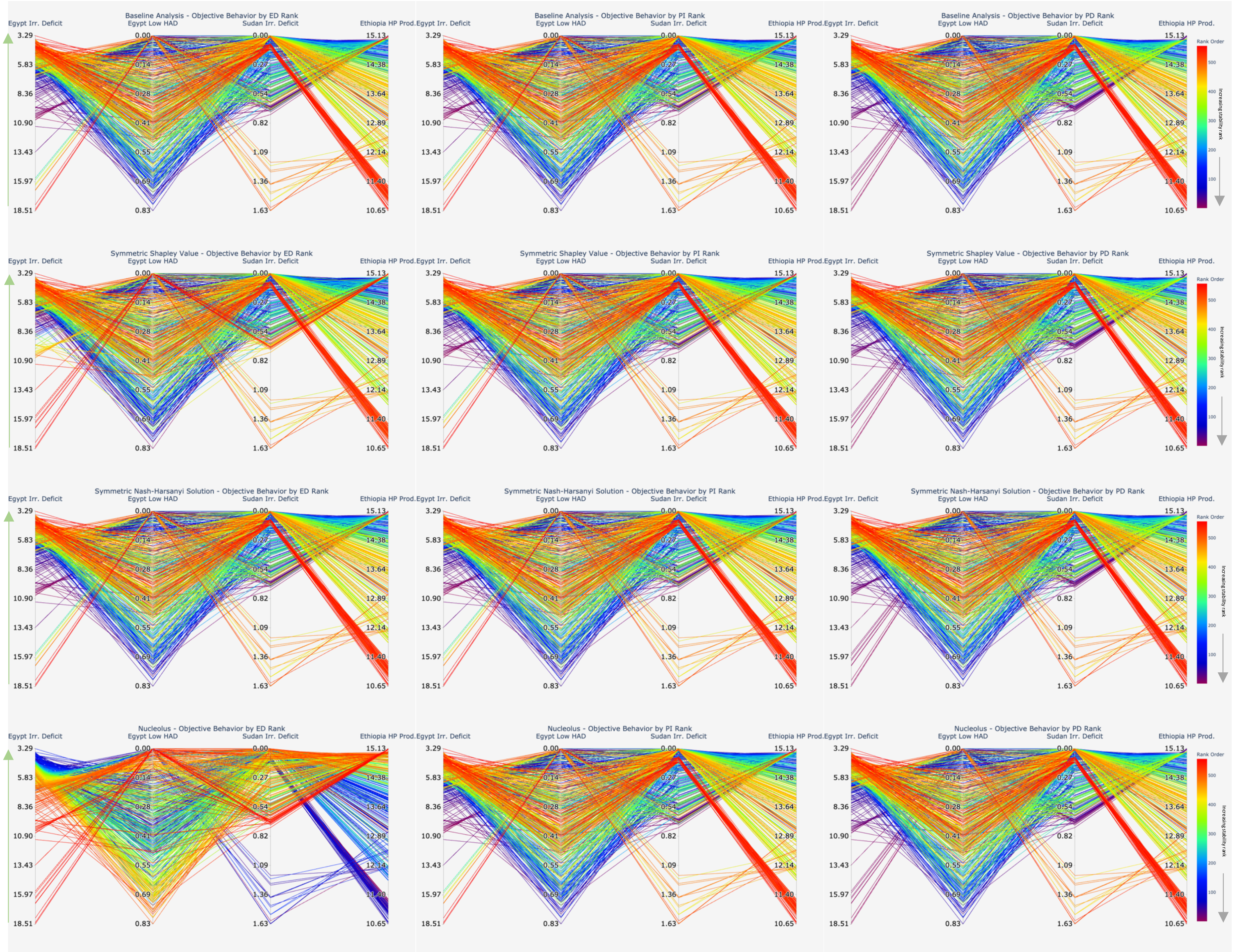
Figure 5.2: A parallel coordinate plot of the Pareto-set of policy candidates from a baseline optimization of the *Eastern Nile Optimization* model. The colored lines each represent a policy that either optimize a specific objective relevant to the stability analysis or were determined to be compromise policies based on minimum percentile/absolute thresholds. All preferred objectives are seen as upper values. Highlighted axes indicate the objectives were used for assessing stability. This value was generated, with new data, based on an original setup by Sari (2022).

The baseline analysis portrays a very distinct trade-off between Egyptian irrigation and Ethiopian hydropower interests. Policies that optimize the irrigation deficit levels for Egypt deliver among the worst GERD hydropower production rates. The *Best Egypt Irr.* policy is among the best to show this trade-off, as the GERD would only be able to produce roughly 11.35 TWh per year of electricity (1.7 TWh per year below its average). Interestingly, the *Best Ethiopia HP* policy actually results in moderate deficit levels for Egypt's irrigation objectives, which highlights a difference large difference in the optimizing policy's impact on the rival nation. The *Best Sudan Irr.* policy delivers among the highest preferred values among the chosen policies below for both Ethiopia and Egypt. Although, it does end up causing moderate frequencies of HAD low-water levels. The *Percentile Threshold* and *Absolute Threshold* policies show similar patterns for each objective; the biggest difference occurs in the HAD low-water level frequencies.

Figure 5.3 (a) and (b) shows more detailed information on trade-offs for by major solution concepts and stability metric. For the baseline analysis, we direct attention to the first row of each figure. The most stable policies (when ranked by Euclidean distance) follow a similar pattern with allocation values for Egypt between USD (5.4-5.55) billion per year. This translates from low-moderate deficit levels (between 8-10 BCM per year) for Egypt. All stable policies will favor high GERD hydropower production levels. Stable policies also show a potential internal conflict in Egypt between HAD hydropower production and irrigation deficits. This could occur, for instance, when the HAD must release water to fulfill a large irrigation deficit from the main Nile stem, which would reduce HAD water levels and truncates the HAD's hydropower production. They show split behavior; some stable policies cause Egypt irrigation deficits values on the lower end of the range and, due to this conflict, produce very large HAD low-water levels frequencies. Alternatively, highly stable policies also deliver slightly higher deficit values for Egypt, which translate to very low HAD low-water levels frequencies (between 0 and 10 percent). However, both of these behaviors for stable policies will still produce very high hydropower production for Ethiopia. This internal conflict will be seen in all solution concepts. Furthermore, the stable policies also result in moderate irrigation deficits for Sudan in a potential trade-off with Ethiopia.

The unstable policies, alternatively, have much more variance. As seen in the diverging behavior (red lines), the unstable policies either entail maximizing utility for either Egypt or Ethiopia while incurring the reciprocal effect on the other nation. Most unstable policies, however, give preference to maximizing Egypt's utility. The major differences in the distribution of objectives, compared to the most stable policies, are a complete optimization of Egypt and Sudan's irrigation deficits and a subsequent minimization of Ethiopia's hydropower generation. However, these policies will also produce a very large range of HAD low-water level frequencies (between 10 and 50 percent).

Ranks based on the PD metric produced the same behavior of highly stable policies. They prioritized low frequencies of HAD low-water levels (although relatively higher than frequencies observed in the most stable policies by Euclidean distance). Ranks between stability metrics (Appendix D.2), are shown to be mostly static. Minor movements in rank order occur between power index and PD indices; however, upon review, these are negligible differences between the numerical values. This would indicate that, despite rank order, policies that are close in metric value would operate similarly, assuming a standardized total utility value. For the baseline analysis, this indicates a mostly proportional relationship between all three metrics.


Baseline Analysis - Objective Behavior by ED Rank
Baseline Analysis - Objective Behavior by PI Rank
Baseline Analysis - Objective Behavior by PD Rank
Symmetric Shapley Value - Objective Behavior by ED Rank
Symmetric Shapley Value - Objective Behavior by PI Rank
Symmetric Shapley Value - Objective Behavior by PD Rank
Symmetric Nash-Harsanyi Solution - Objective Behavior by ED Rank
Symmetric Nash-Harsanyi Solution - Objective Behavior by PI Rank
Symmetric Nash-Harsanyi Solution - Objective Behavior by PD Rank
Nucleolus - Objective Behavior by ED Rank
Nucleolus - Objective Behavior by PI Rank
Nucleolus - Objective Behavior by PD Rank
Egypt Irr. Deficit
Egypt Low HAD
Sudan Irr. Deficit
Ethiopia HP Prod.
3.29
5.83
8.36
10.90
13.43
15.97
18.51
0.00
0.14
0.28
0.41
0.55
0.69
0.83
0.00
0.27
0.54
0.82
1.09
1.36
1.63
15.13
14.38
13.64
12.89
12.14
11.40
10.65
Rank Order
500
400
300
200
100
Increasing stability rank

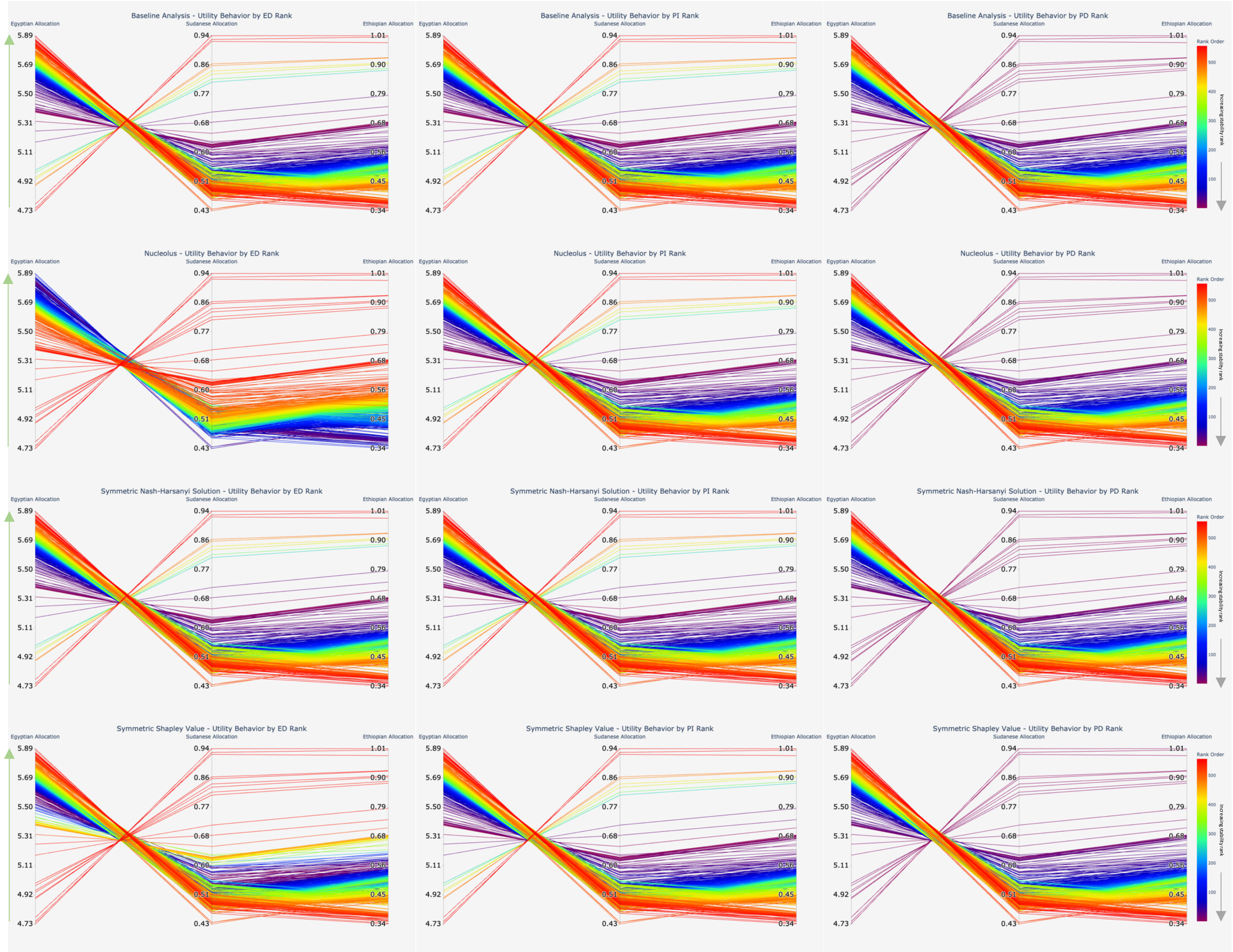

Baseline Analysis - Utility Behavior by ED Rank
Baseline Analysis - Utility Behavior by PI Rank
Baseline Analysis - Utility Behavior by PD Rank
Nucleolus - Utility Behavior by ED Rank
Nucleolus - Utility Behavior by PI Rank
Nucleolus - Utility Behavior by PD Rank
Symmetric Nash-Harsanyi Solution - Utility Behavior by ED Rank
Symmetric Nash-Harsanyi Solution - Utility Behavior by PI Rank
Symmetric Nash-Harsanyi Solution - Utility Behavior by PD Rank
Symmetric Shapley Value - Utility Behavior by ED Rank
Symmetric Shapley Value - Utility Behavior by PI Rank
Symmetric Shapley Value - Utility Behavior by PD Rank
Egyptian Allocation
Sudanese Allocation
Ethiopian Allocation
5.89
5.69
5.50
5.31
5.11
4.92
4.73
0.94
0.86
0.77
0.68
0.60
0.51
0.43
1.01
0.90
0.79
0.68
0.56
0.45
0.34
Rank Order
500
400
300
200
100
Increasing stability rank

Figure 5.3: A multi-panel plot of various parallel coordinate plots showing the (**a**, *top multipaned plot*) distributions of objectives and (**b**, *bottom multipaned plot*) distribution of utilities of different Pareto-set policies. For each panel, each row refers to a different solution concept or focal point: in order from top to bottom, the Baseline Analysis, symmetric Shapley Value, symmetric Nash-Harsanyi solution, and the nucleolus. Each column will refer to a different stability metric: in order from left to right, Euclidean Distance (ED), the Leohman Power Index (PI), and the propensity to disrupt (PD). For each plot in all panels, the desirable objective value is always the upper value; direction of preference is given by the green arrow. The color pallet indicative of the rank of a particular policy, where rank order is most stable (rank of 1, *purple*) to least stable (rank of 557, *red*). **Axis units for (a):** *Egypt Irr Deficit* [BCM per year]; *Egypt Low HAD* [percent]; *Sudan Irr Deficit* [BCM per year]; *Ethiopia HP Prod.* [TWh per year]. **Axis units for (b):** all axes are in [USD billion per year].

5.3.1 PD AND POWER INDEX RANKINGS

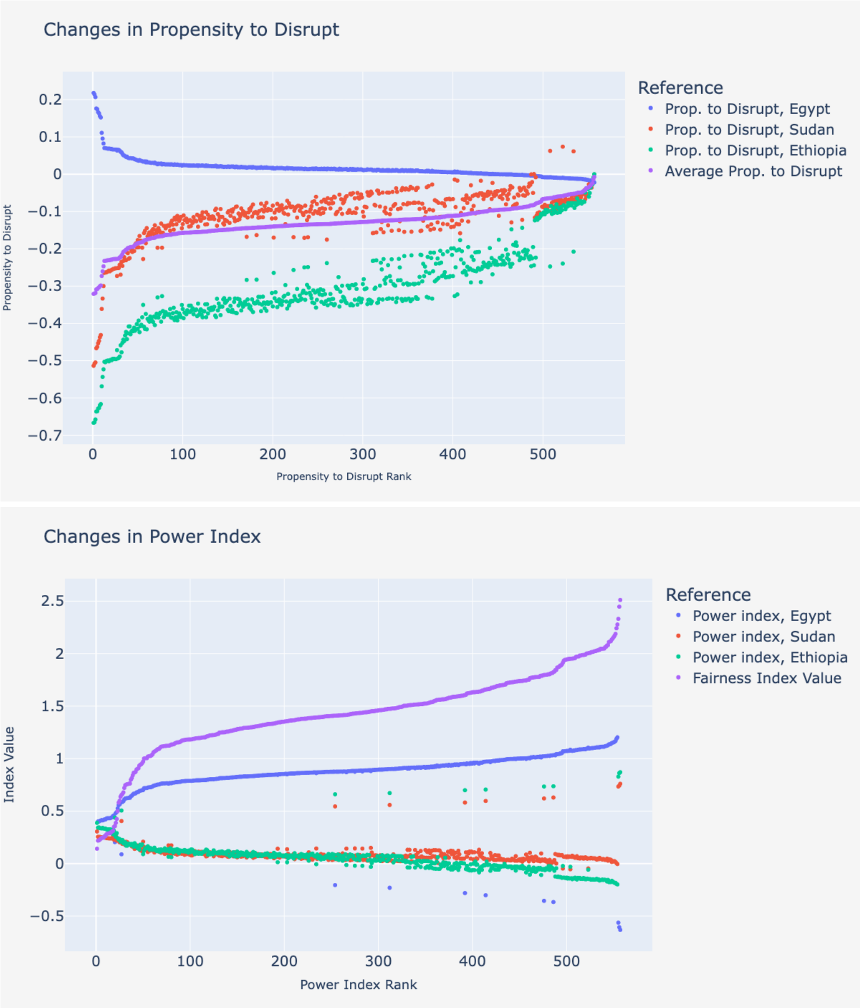


Figure 5.4: Individual and aggregated (**a**, *top plot*) propensity to disrupt and (**b,** *bottom plot*) power index values based on respective ranking of policies.

The progression of power index and propensity to disrupt (PD) across all solution concepts remains the same. To explore this, we briefly explain Figure 5.4 (a) and (b), which shows the progression of PD and modified power index values (along with their respective aggregated values used to determine rank). Unlike Euclidean distance, the power index and PD values were two stability metrics whose values do not have a changing focal point as a parameter. Instead, these are calculated for each individual policy candidate in the Pareto-set. Because of this property, they were used to place context of each nation's actions based on rankings determined by Euclidean distance.

The purple points in Figure 5.4(a) show the movement of average PD values. As policies become more unstable, average PD values are driven primarily through increases in individual PD values from Sudan and Ethiopia. This means that their individual expected losses, compared to the expected losses of the other nations in the grand coalition in the event of their defection, is smaller. Thus, it creates a higher incentive to defect for these nations since their loss has a smaller magnitude. Theoretically, this gives Ethiopia and Sudan greater negotiating power in these policies, especially when considering that Egypt's PD value consistently drops in unstable policies. For power index values, there exists a similar progression. Egypt's power index values increase at a higher gradient as policies become more unstable and as the analogs of Sudan and Ethiopia gradually decrease. The fairness index's accelerated increase indicates the quick growth of the standard deviation of power indices.

The steep incline of power index and PD values for all nations at high rank values in Figure 5.4 were determined to represent boundary error policies. These are policies with seemingly large movements in rankings due to large magnitudes of competing individual PD values. These were also policies that allocate abnormally high utility ratios to Ethiopia and Sudan and similarly low utility ratios to Egypt. When cross-referencing these specific policies with the non-standardized Pareto-set of objectives, these were also the policies with the lowest policy efficiency, meaning that they are the worst at maximizing the possible utility of the grand coalition.

5.4 SHAPLEY VALUE

5.4.1 SYMMETRIC SHAPLEY VALUE

While the symmetric Shapley Value produced similar behavior as the baseline analysis, there are a few unique insights. Figure 7(b) depicts that the most stable policies (by Euclidean distance) under the symmetric Shapley Value mostly allocate high utility values to Egypt, between USD (5.5-5.6) billion per year. They also achieve a narrow but high range in Ethiopian utility, ranging from USD (0.55-0.6) billion per year. Sudanese allocations follow suit and actually have the same range of utility amounts as Ethiopia. The most stable policies also have relatively smaller ranges for Egypt and Sudan's irrigation deficits (compared to the baseline analysis) and achieve close to the highest Ethiopian hydropower production capacities. Using the symmetric Shapley Value as the reference solution tightened the range of possible allocations for all nations when considering the most stable policies. This implies that these policies are similarly designed in terms of their utility and objective distributions. Compared to the baseline analysis, the symmetric Shapley Value also provided stronger allocations for Egypt while decreasing Ethiopia and Sudan's allocations. This could be explained by each component of the symmetric Shapley Value's solution being in the vicinity of a large number of policy candidates with similar component values. Nonetheless, by basing a rank order on the symmetric Shapley Value using Euclidean distance, Egypt holds an advantage in having a slightly better utility; however, they are disadvantaged by relatively rigid range of utility it can potentially receive.

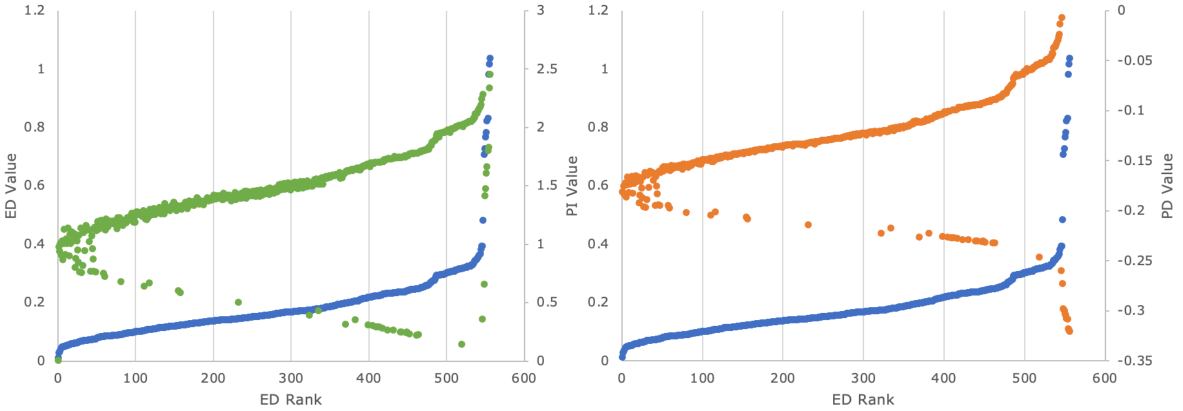


Figure 5.5: The values of the power index (green) and the PD (orange) plotted in order of ED ranking for the symmetric Shapley Value.

Figure 5.5 shows the trends of power index and PD values when ordered by the symmetric Shapley Value's Euclidean distance-based rank. A direct relationship between both the power index/PD values and Euclidean distance is shown. As policies become more unstable, differences between the symmetric Shapley Value and Egypt's allocation in a specific policy grow at a faster rate (in Egypt's direction of preference) as compared to that of Ethiopia or Sudan. Power index value is propelled entirely by a growing standard deviation of individual power indices, as the mean remains constant (equation. Similarly, PD value progression based on ED rank ordering show interesting dynamics. Average PD, which determines its rank order, grows primarily as a result of Sudan and Ethiopia's increased PD value, indicating a greater threat from these two nations to the grand coalition. The only way this would be possible is due to the growth in allocations for Egypt.

In short, by using the symmetric Shapley Value as the reference solution, the policies that are deemed unstable by Euclidean distance are characterized by large inequalities in gains from allocations. Furthermore, they also observe increased threats to negotiations from Ethiopia and Sudan because of these inequalities. While stable policies see less of this threat, Egypt's motivation to collaborate is also minimized due to it receiving some of the lowest allocations amongst policy candidates.

5.4.2 Weighted Shapley Value

To simulate changes in the coalition probability weights, we created three problem formulations based on various geopolitical characterizations across the three ENB nations. This is a representation of varying perceptions on different coalitions that each nation may have. These problem formulations include a joint effort between Egypt and Sudan acting unilaterally against Ethiopia (1), full cooperation against all nations (2), and, as has been seen in recent years, a coalition between Sudan and Ethiopia against Egypt (3). Probability weight tables are given below. Due Egypt and Ethiopia's routine and heated disagreements on water allocations, a coalition solely between these two nations has a very low probability; therefore, we assume a weight of zero wherever applicable in all three problem formulations. Table 5.2 shows the probability weights used for each coalition for all problem formulations.

PROBLEM FORMULATION 1: (EGYPT & SUDAN) VS. ETHIOPIA

For Problem Formulation 1, Egypt and Sudan have historically been aligned against potential infringements on Nile water access (Wheeler et al., 2018). We assume that this alliance continues to optimize Egyptian and Sudanese objectives. Egypt depends on Sudan's cooperation as a humanitarian justification for the harmful downstream effects that the GERD poses. Likewise, Sudan relies on Egypt's regional hegemony, as it has in the past, to leverage large releases from Ethiopia to fulfill their irrigation and hydropower demands. Thus, highest probabilities are placed on these nations' coalitions to show unilateral action. However, Sudan and Ethiopia are aware of flooding problems that result from no upstream barriers. Therefore, indicated by weights associated with Sudan-Ethiopia coalitions, there is a small probability of a coalition. However, the rivalry between Egypt and Ethiopia means that, in the event of Sudan's partnership with the rival nation, each will have little probability of joining the grand coalition.

PROBLEM FORMULATION 2: FULL COOPERATION IN THE ENB

For Problem Formulation 2, all ENB nations are actively working with the Nile Basin Initiative (NBI) to find solutions that benefit all nations. In this case, both Egypt and Ethiopia, while not actively forming a coalition solely between themselves, will join the grand coalition in the event that the other two nations succeed in forming a sub-coalition. They also acknowledge that allocations are most likely going to negotiated through the grand coalition, and thus assign lower probability weights to joining sub-coalitions in anticipation of forming the grand coalition. Sudan, alternatively, acts as the broker between both countries. They denote equal weight in joining either Egypt or Ethiopia in a coalition with the intent to motivate the outlying member into step into negotiations.

PROBLEM FORMULATION 3: EGYPT VS. (SUDAN AND ETHIOPIA)

Problem Formulation 3 is designed to be the opposite of Problem Formulation 1. Because of the devastating flooding events in Sudan, there has been recent recognition on the benefits of the GERD (Asefa, 2020). To prevent economic loss, Sudan secures an alliance with Ethiopia. Ethiopia sees the benefit of Sudan's alliance, as this would allow for near maximum operation of the GERD. Furthermore, this also helps secure funding for future water infrastructure projects (Wu and Whittington, 2006; Arsano and Tamrat, 2005). Egypt, therefore, protests this coalition. While they anticipate being on their own in a sole-member coalition, Egypt's historic, religious, and environmental ties with Sudan allow it to place a moderate weight on joining a coalition only if Sudan is present. However, it still has relatively small interests in joining the grand coalition if Sudan and Ethiopia have already agreed to maximize their joint utility.

Table 5.2: Probability weights for (a, *top*) Problem Formulation 1, (b, *middle*) Problem Formulation 2, and (3, *bottom*) Problem Formulation. Nations inside brackets indicate constituents of a coalition prior entry of the particular nation. Each column represents the probability weights that a nation (specified above) has for a specific coalition that they are party to.

Egypt		**Sudan**		**Ethiopia**	
Coalition {S-i} i	**Weight**	**Coalition {S-i} i**	**Weight**	**Coalition {S-i} i**	**Weight**
{∅} Egypt	0.2	{∅} Sudan	0.2	{∅} Ethiopia	0.7
{Sudan} Egypt	0.7	{Egypt} Sudan	0.7	{Egypt} Ethiopia	0
{Ethiopia} Egypt	0	{Ethiopia} Sudan	0.1	{Sudan} Ethiopia	0.2
{Sudan, Ethiopia} Egypt	0.1	{Egypt, Ethiopia} Sudan	0.1	{Egypt, Sudan} Ethiopia	0.1
Coalition {S-i} i	**Weight**	**Coalition {S-i} i**	**Weight**	**Coalition {S-i} i**	**Weight**
{∅} Egypt	0.2	{∅} Sudan	0.2	{∅} Ethiopia	0.2
{Sudan} Egypt	0.2	{Egypt} Sudan	0.35	{Egypt} Ethiopia	0
{Ethiopia} Egypt	0	{Ethiopia} Sudan	0.35	{Sudan} Ethiopia	0.2
{Sudan, Ethiopia} Egypt	0.6	{Egypt, Ethiopia} Sudan	0.10	{Egypt, Sudan} Ethiopia	0.6
Coalition {S-i} i	**Weight**	**Coalition {S-i} i**	**Weight**	**Coalition {S-i} i**	**Weight**
{∅} Egypt	0.6	{∅} Sudan	0.2	{∅} Ethiopia	0.1
{Sudan} Egypt	0.25	{Egypt} Sudan	0.1	{Egypt} Ethiopia	0
{Ethiopia} Egypt	0	{Ethiopia} Sudan	0.7	{Sudan} Ethiopia	0.7
{Sudan, Ethiopia} Egypt	0.15	{Egypt, Ethiopia} Sudan	0	{Egypt, Sudan} Ethiopia	0.2

Figure 5.6 (a) through (c) shows the visual distribution of the different problem formulations. Overall, there are a few observations. In general, unstable policies mimic the symmetric Shapley Value's behavior and deliver a split behavior on irrigation demand deficits to Egypt, moderate irrigation deficits to Sudan, and very low Ethiopian hydropower production. The most stable policies' behaviors change with the problem formulation. Looking first at Figure 5.6(a), Problem Formulations 1's stable policies have larger range of allocation amounts for Egypt with respect to the symmetric solution. Problem Formulations 2's pattern is not very clear; both problem formulations' most stable policies deliver very low hydropower generation capabilities to Ethiopia (in the same range of 12-13 TWh per year). Problem Formulations 3's utility distribution shows a larger set of stable policies prioritizing higher Ethiopian and Sudanese utility, similar to the symmetric Shapley Value.

We also examined the distribution of stability metric values based on the ED metric ranking (shown in Appendix F.3). Problem Formulations 1 and 2 distributions show a considerable amount of variance in the power index and PD rankings. This may be related to distance; among the three problem formulations, problem Formulation 1 had the farthest distance from policy candidates. It also placed Egypt and Sudan in strong positions by placing higher probabilities on coalitions with high corresponding characteristic values. Despite Problem Formulations 1's stable policies heavily rewarding Egypt, allocations actually fell for Sudan as policies became less stable. It shows that a coalition between them did not create equal benefits for all nations in this coalition. Problem Formulation 2's variance is explained similarly; however, it's solution also had significantly less variance between nation's allocation. Problem Formulations 3 virtually had no variance and was similar in behavior to the symmetric Shapley Value.

When demonstrating changes in coalition perceptions between the different nations, we see that coalitional perceptions that hurt Ethiopia (as in Problem Formulations 1) have severe consequences for them. However, coalitional perceptions against Egypt do not inflict the same level of damage. Sudan's impact is not as obvious as its neighbors and can benefit from further study. Despite Egypt's dominance on utility allocation, a coalition between Sudan and Ethiopia certainly helps expand the negotiation space to choose policies that are even more beneficial to them.

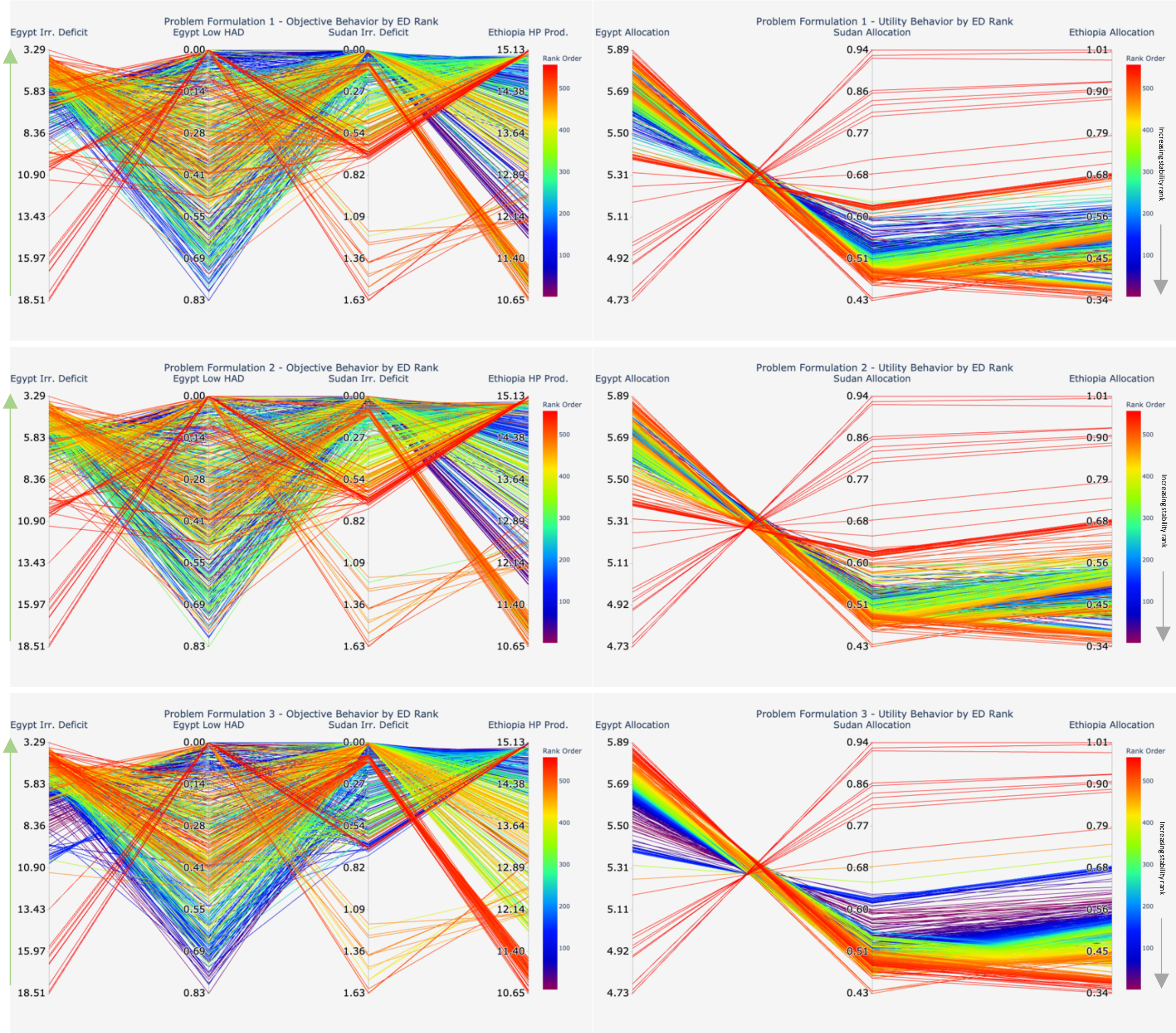


Figure 5.6: For each problem formulation (1 to 3 from *top to bottom*), a parallel coordinate plot distribution of the most stable and least stable policies. (a, *left plots*) Objective distributions and (b, *right plots*) utility distributions between each policy, ranked by Euclidean Distance value, are shown. There are differences in the each's nation's ranges on most stable allocations; overall behavior remains similar for all formulation. For each plot in all panels, the desirable objective value is always the upper value; direction of preference is given by the green arrow. The color pallet indicative of the rank of a particular policy, where rank order is most stable (rank of 1, *purple*) to least stable (rank of 557, *red*).

5.5 NASH-HARSANYI SOLUTION

5.5.1 SYMMETRIC NASH-HARSANYI SOLUTION

Surprisingly, using the symmetric Nash-Harsanyi solution led to Euclidean distance-based policy candidate behaviors identical to those from the baseline analysis. By extension, this also meant that the rank orders across all metrics was also identical. It should be noted that there is a short distance between the characteristic values and this solution, which could explain why relative rankings remained unchanged.

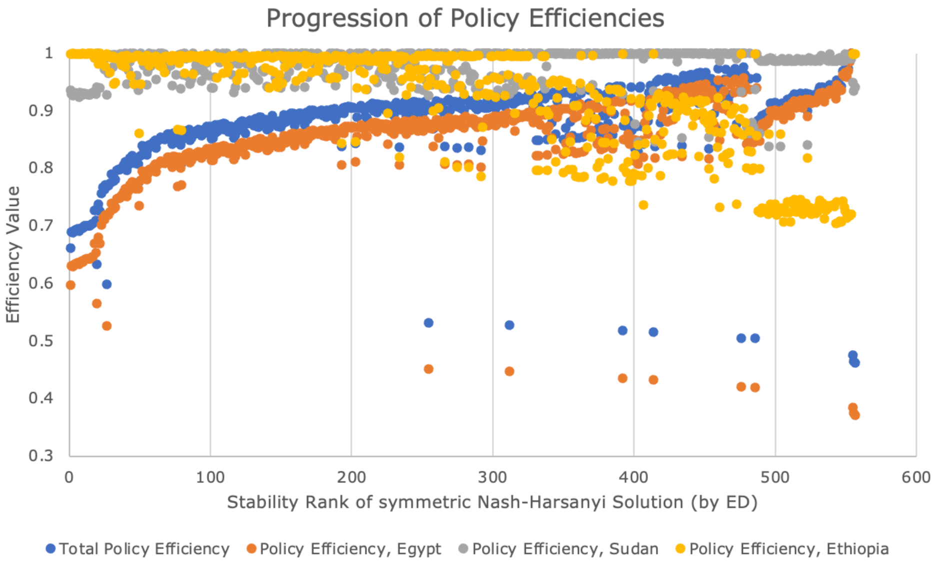


Figure 5.7: The trends of total policy efficiency and individual policy efficiencies plotted against the Euclidean distance-based stability rank order for the symmetric Nash-Harsanyi solution. More unstable policies are characterized by high total policy efficiency and are closely aligned with the pattern of Egypt's utility. Alternatively, a decline in Ethiopia's policy efficiency is also seen, indicating that it sees reduced utility allocations as policies become more unstable. Sudan's efficiency is mainly stable.

Figure 5.7 brings insight into the policy efficiency behavior of different policy candidates. Efficiency values for the most stable policies ranged between 0.66 and 0.75. This implies that nearly one third of potential total utility is lost when decisionmakers pick the most stable policies with the symmetric Nash-Harsanyi solution as the reference solution. As policies became unstable, the total utility tends to increase. This affirms Read et al. (2014)'s statement regarding the disconnect between solution optimality and stability.

Table 5.3: Policy candidates that give the lowest policy efficiency values (or the prices of anarchy) for different ENB nations. The bolded numbers indicate the efficiency level for each nation, where the efficiency is the policy candidate's individual allocation as a ratio of the maximum utility allocated amongst all policies. The blue highlighted row shows Egypt's price of anarchy after accounting for boundary error policies.

Policy Candidate	Total Efficiency	Policy Efficiency, Egypt	Policy Efficiency, Sudan	Policy Efficiency, Ethiopia
38	0.4622	**0.3711**	0.9415	0.9985
304	*0.6612*	***0.5973***	*0.9409*	*0.9983*
537	0.8981	0.8852	**0.8377**	0.8593
267	0.9291	0.9211	0.9867	**0.7037**

We can also look at the progression of each nation's individual efficiencies to see how inefficient a policy may be from their maximum achievable allocation from the Pareto set. Efficiency growth plateaus for Egypt in less stable policies. We also see a reduction in Ethiopia's efficiency with higher variance, while Sudan's efficiency effectively stays constant. Table 5.3 shows specific prices of anarchy for each nation. For this, we refer back to the assumption that in a cooperative setting, utility obtained from strategic or non-cooperative strategies would be outweighed by those obtained from coalitions. The price of anarchy for Egypt is significantly lower than analog values for the other countries. When accounting for boundary error policies, Egypt suffers a 40 percent loss in efficiency from working in a non-cooperative setting. The same policy generates high efficiencies for others, implying a significant disadvantage for Egypt if this equilibrium is used. Ethiopia and Sudan's prices of anarchy are comparatively higher, which may indicate that the aversion to strategies that entail such levels of equilibrium would be much less. In this policies, we also see high individual efficiencies for other nations. Combined, we find that as policies become less stable (when ranks are based on policy efficiency), policy efficiency becomes very closely tied to the progression of Egypt's individual policy efficiency. Since its efficiency values imply significant disadvantages for Egypt, it may reduce the feasible policy subset from the Pareto-set where each nation's efficiency expectations are fulfilled.

5.5.2 ASYMMETRIC NASH-HARSANYI SOLUTION

To account for differences in bargaining powers in negotiations, asymmetric Nash-Harsanyi solutions were developed using Equation 3.3.10. Calculating precise individual bargaining weights, similar to probability weights for coalitions, requires knowledge on the geopolitical and socioeconomic contexts that may factor into a negotiation (Fu et al., 2018). As a simplification, we used mathematical scenarios to create various combinations of bargaining weights. Theoretically, this information could be used by researchers who are able to quantify the necessary information into a normalized bargaining weight for each nation. Each scenario entails making one of the ENB nations as a "dominant" player, meaning they have the greatest power in a round of negotiations. For each scenario, the dominant player would receive a minimum bargaining weight of 0.5 (assuming a sum of 1 for all weights). Each combination of bargaining weights produces a different solution allocation. Dominant player bargaining weights were simulated to go to complete domination (a bargaining weight of 1), although this scenario is unlikely. The main insights from each scenario are discussed below. Figure 5.8 shows spatial distributions of the asymmetric Nash-Harsanyi solutions.

SCENARIO 1: EGYPT AS THE DOMINANT PLAYER

Placing Egypt as the dominant player will exacerbate the behavior that were seen previously with other CGT solution concepts. Increases in Egypt's bargaining weight gradually move the Nash-Harsanyi solutions closer to the epicenter of the policy candidate cluster. Furthermore, the most stable policies became those that almost exclusively prioritized high utility allocations for Egypt. Recall that policy efficiency becomes closely tied with Egypt's utility amount. Therefore, we expectedly also witness stable policies characterized with increasingly high efficiencies as Egypt's bargaining weight rises. Simultaneously, the Egypt and Ethiopia utility ranges seem to tighten their width. Egypt irrigation deficit tighten as well, leading to a lower deficit.

Despite this, there are not very dramatic changes for Ethiopia's respective utility or objective allocations. Stable policies under an Egyptian bargaining dominance only slightly drop from the maximum Ethiopia hydropower production levels. On the other hand, Sudan's utility is significantly reduced by larger Egyptian bargaining weights. The transition between a bargaining weight of 0.5 to

0.9 caused a reduction of nearly USD 0.2 billion per year in Sudan's utility (Appendix G.3). When analyzing power index values ordered by Euclidean distance rank, larger variances are seen in more stable policies as bargaining weight rises, which confirms Egypt's "runaway" utility behavior seen previously. In short, stable policies that are observed with high bargaining weights for Egypt have large impacts on limiting the flexibility on allocation amounts to all nations.

SCENARIO 2: SUDAN AS THE DOMINANT PLAYER

The asymmetric Nash-Harsanyi solutions produced under Sudanese dominance are not nearly as integrated into the general policy candidate population as seen in Scenario 1. When Sudan acts as the dominant player, there are not very clear distinctions as the bargaining weights increase. Rank orders across different stability metrics effectively stay constant. Much of this is probably attributed to the distance from the general policy candidate space. Therefore, the rank order does not change significantly due to relatively small shifts in values associated with the increase in bargaining weight. The only visible benefit to an increase in bargaining weight, similar to Egypt's case, is that policies that allocate high amounts to Sudan are clustered near the front of the ED rank order (Appendix G.5). This implies that Sudan's preferred policies would have a higher probability of being one of the most stable policy. Otherwise, Sudan's trade-offs in objectives and utility distributions are similar to those seen in earlier solution concepts.

SCENARIO 3: ETHIOPIA AS THE DOMINANT PLAYER

Setting Ethiopia as the dominant player shows a similar phenomenon of distance from the policy candidate set as seen in Scenario 2. Despite Ethiopia's real-life leverage as the headwater state in the ENB, increasing its bargaining weights does not produce major differences in the order of policy stability for this specific set of policy candidates. Again, much of this can be attributed to the distance from the policy candidate set and very small changes in stability metrics observed between certain policies. The only benefit seen with the increase in bargaining weight was similar to what Sudan experienced. As bargaining weight increases, policy candidates that were low in stability rankings transitioned to near the top, essentially meaning that a greater ratio of highly stable policies involve high utility allocations to Ethiopia.

Furthermore, when looking at the progression of power index and PD values, a higher bargaining weight also shifts policies towards the front of the rank order that show negative power index values for Egypt. These policies are those where Egypt would have a preference of collaborating. Interestingly, a different interpretation is given through the PD values, which indicate that Egypt has the relatively high propensity to disrupt at the most stable policy. Overall, the asymmetric Nash-Harsanyi solutions indicate that, given a dominant player who does not have high contributions to a coalition's characteristic value, they must have immense bargaining power or risk a small set of policies that would be acceptable by all players.

Figure 5.8: Bathycentric plots showing the distribution of asymmetric Nash-Harsanyi Solutions with (**a**, *top left plot)* Egypt, (**b,** *top right plot*) Sudan, and (**c**, *bottom plot*) Ethiopia as the dominant player. The movement of Nash-Harsanyi solutions are identified through the dominant player's bargaining weight. The arrows show the movement between the remaining bargaining weight between the other two nations.

5.6 NUCLEOLUS

The nucleolus was found with an ε value of 0.063, which was identical to the ε value required to establish the ε-Core. Since the nucleolus is always in the Core (assuming it exists), this indicates a relatively small deduction from coalition characteristic values necessary for the solution to become acceptable. The most stable policies for the nucleolus, compared to other behaviors in Euclidean distance-based ranks, are similar to other solution concepts with respect to optimizing Egyptian irrigation deficit. However, the nucleolus's stable policies follow an extreme version of this behavior. Figure 7a shows most stable policies are optimizing Egyptian irrigation deficits, averaging about 4.1 BCM per year. The same can be observed for Sudan's irrigation deficit (approximately 0.1 BCM per year of deficit). The most unstable policies follow similar patterns across different objectives as seen in previous solution concepts. For these policies, a large range of moderate-to-severe Egypt irrigation deficit values is clearly seen, resulting in a maximum utility difference of USD 0.6 billion per year. Despite this long range, HAD low-water level frequencies do not exhibit as dynamic of movements and are confined to very low levels. Moderate Sudan irrigation deficit values also exist with a range of USD 0.24 billion per year, all of which lead to a maximization of Ethiopia's hydropower output.

For the most stable policies, the biggest difference is that the GERD's hydropower production is near minimum levels, with few policy candidates with high stability allowing for even moderate production levels. Upon further review, policy candidates with higher GERD hydropower production levels effectively siphon this benefit by imposing more severe irrigation deficits for Sudan.

6. DISCUSSION

6.1 CUMULATIVE INSIGHTS AND SUMMARY

The main aim of this research was to assess various methods for determining the relative stability of solutions in the Pareto-optimal set, utilizing both CGT solution concepts and stability metrics. Research sub-question (b) was formulated to guide the discussion, which explores differences in objective and utility distributions among the subset of stable policies derived from each solution concept-stability metric combination. In this section, we summarize some of the key observations made in the previous analysis.

The overall behaviors of utility distributions in most solution concepts remained similar to the baseline analysis. For the baseline analysis, policy candidates determined to be most stable by Euclidean distance were strongly characterized by prioritizing Ethiopian hydropower production levels. This was allowed, however, because the stable policies also resulted in moderate irrigation deficit levels to Egypt (approximately 10 BCM per year) and among the highest irrigation deficit values of any policy candidate to Sudan (between 0.7 – 0.73 BCM per year). These policies also prioritized HAD low-water level frequencies, which were consistently being traded off with Egypt's irrigation deficit values. Unstable policies were characterized by starkly opposite patterns, either maximizing or minimizing Egypt irrigation deficit values and performing its reciprocal behavior with Ethiopian hydropower production values. However, as a general observation, **more unstable policy candidates saw a stark trade-off between Egypt's irrigation deficit and Ethiopia's hydropower production objectives.** For most unstable policy candidates in the baseline analysis, this usually meant a preference to minimize Egyptian irrigation deficit levels (or maximize Egyptian utility) and minimize Ethiopian hydropower production, but this division was more prominent in other solution concepts. This also meant that **unstable policies were those that completely optimized either nation's objectives to the full detriment of the other.**

Using the symmetric Shapley Value as the reference solution showed most stable policies (by Euclidean distance) also characterized by high Ethiopia hydropower values. These stable policies formed tighter ranges of utility allocations for all three nations and less robust trade-offs, particularly between Sudan's irrigation deficit and Ethiopian hydropower production. Weighted Shapley Values, in general, mimic the symmetric Shapley Value's utility and objective behaviors. We did notice, however, that having probability weights that reflected coalitional perceptions against Ethiopia showed large negative ramifications for Ethiopian allocations for the most stable policies; perhaps by the large magnitude of Egypt's expected allocations, similar effects were not seen when probability weights reflected perceptions against Egypt. The symmetric Nash-Harsanyi solution produces the same Euclidean distance rank order as the baseline analysis and also gave insight on the relatively small policy efficiencies that the most stable policy candidates possessed. Asymmetric solutions, except Scenario 1, produced similar results to the symmetric Nash-Harsanyi solution. Scenario 1's ranks changed mainly as Egypt's bargaining weight grew. Finally, the nucleolus produced distinct results based on Euclidean distance, and also had the greatest rank change amongst the stability metrics with a complete reversal in rankings when ordered by PD or power index values. This was driven by its extreme behavior in preferring policies that gave large allocations to Egypt while completely minimizing Ethiopian hydropower production and utility.

6.2 CONSISTENCY BETWEEN POWER INDEX AND PD RANK ORDERS

In Section 5.3, the power index and PD stability ranks were discussed. As a brief reminder, when not considering the boundary error policies, the power index progression showed significantly larger equality between each nation’s gain from an allocation (relative to their characteristic value) in the most stable policies. A similar rank order for the PD metric showed that Egypt’s PD was at nearly its highest point when policies were most stable while Ethiopia and Sudan’s PD values indicated a strong desire for collaboration. As policies became less stable, mentalities between the nations flipped.

In the ENB’s context, this means that **Egypt’s willingness to cooperate is directly dependent on whether it achieves a sufficient payoff amount from Nile water.** This would be motivated by a gradually higher loss of utility to Egypt as compared to the loss to the grand coalition. Framing it another way, lower irrigation deficit values (or higher utility) for Egypt bring them closer to attaining their “historic” rights they claim for Nile water, which they have repeatedly claimed as justification for not engaging in negotiations with Ethiopia (Mbaku, 2022). However, the policies that relax Egypt’s hardline stance against GERD negotiations are also those that Ethiopia would find unacceptable due to the resulting fill levels for the GERD that would constraint its hydropower capacities (ICG, 2020). This may seem like a point of geopolitical gridlock, but upon further review, Egypt’s PD values, even at the most stable policies, are actually quite low (albeit positive), hovering around 0.1. Wu and Whittington (2006) also note this, explaining that Egypt’s high benefit from most cooperative policies and fears of upstream retaliation place it a good position for negotiations. Thus, due to the comparatively lesser degree of conflicting desirability for cooperation between Egypt and its upstream neighbors, potential negotiations can be less arduous than expected.

6.3 SIMILARITIES BETWEEN SOLUTION CONCEPTS

There the lack of significant change in the behavior of stable policies as the solution concepts were changed. Figure 6.1 shows the spatial representation of the solution concepts overlaid on the policy candidate solution space. Recall that the efficiency constraint was placed when calculating each symmetric solution concept. This constraint allows these particular solutions to be acceptable imputations, given that they remain within the shared space for the marginal contributions of each player. As expected, many of the solution concepts have varying spatial occupation as they have different theories of fairness that underly calculations. For example, the symmetric Shapley Value’s position near the middle of the imputation space is based on both egalitarian and marginalist theories. Regardless, despite the differences in distance between the policy candidates and the various solution concepts, there are not very large movements in rank order of truly stable policies by Euclidean distance (Appendix I.6).

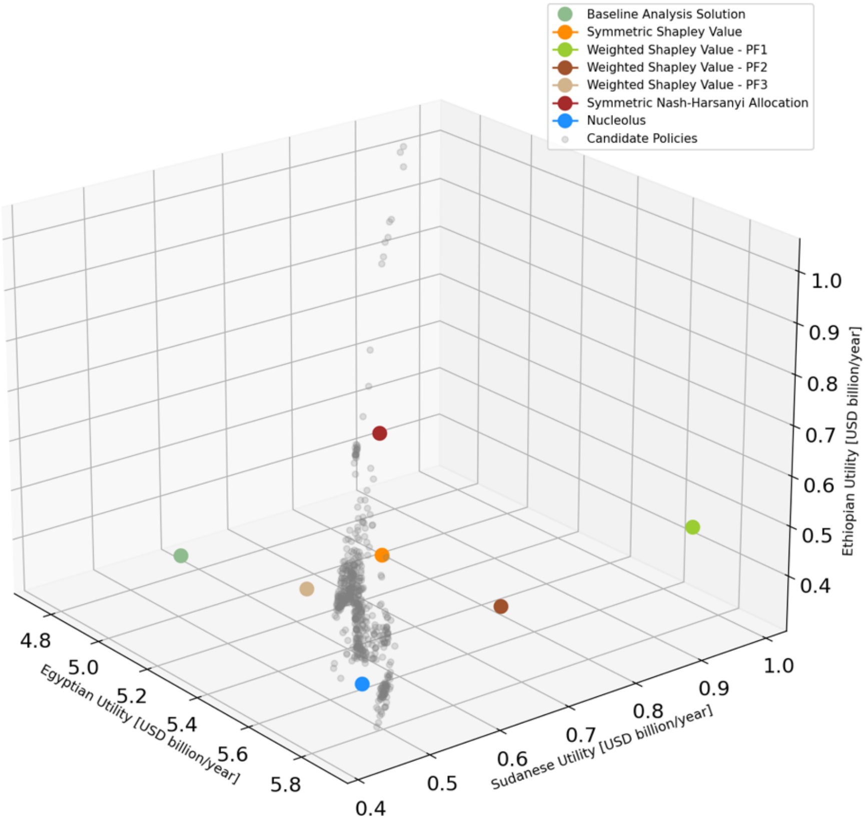


Figure 6.1: A 3D scatter plot showing the spatial distributions of the different solution concepts calculated.

Upon investigation, this could likely be a commensurability issue resulting from the use of the Euclidean distance formula to measure the magnitude of difference. As noted earlier, Euclidean distance has been used as a simple metric for gauging the dissatisfaction of a player based on their distance from their expected utility (Wu and Whittington, 2006; Friedmann et al., 2021). However, by mathematical definition, the distance formula will penalize large deviations from a reference solution. This is regardless of whether that deviation is a result of higher utility allocations than the player expects. Recall our assumption that the ENB conflict is a transferable utility game with an efficiency constraint, essentially meaning that there is a total utility sum that must be achieved for each policy. The Euclidean distance formula, thus, will quantitatively deem policies unstable that (1) either have a very large benefit to or (2) are significantly disadvantaged over other players.

Therefore, the choice to use the distance formula effectively neutralizes most significant (dis)advantages from any player, which is why the policy ranks and, more importantly, policy behaviors do not change significantly. It should be noted that this was one of the possible ramifications of standardizing all policy candidates. By effectively eliminating the potentially large differences in distance between policies, we encountered a phenomenon with both positive and negative consequences. Positive consequences included assessing each policy candidate solely in a relative formation to identify the high stable policies of all in the Pareto set. The negative consequences included a reduction in differences, which would affect distance calculations. For this analysis, use of the Euclidean distance formula eventually leads us to find policies that are the most egalitarian, by quantity of benefit from the solution concept. This is roughly supported by the power index and PD value dynamics that proportionally follow Euclidean distance value progression.

6.3.1 BENEFITS FROM COOPERATION

One of the major outcomes from most solution concepts is that Egypt's utility will grow with a simultaneous drop in Ethiopia and Sudan's utility as policies become less stable. Therefore, one key question for the latter two nations is how to prevent the "runaway" utility effect that Egypt experiences while still having feasible conditions for negotiation. Recall in Problem Formulation 2, it is assumed that the ENB is working in full cooperation. Problem Formulation 2, in comparison to the other weighted Shapley Value solutions, resulted in a smaller range of stable utilities for all nations (Appendix F.4). Egypt's utility increases are actually quite moderate in comparison to other problem formulations. At the same time, Ethiopia's utility increases which, although with quite more variance, is not seen in other problem formulations. If we reference policy efficiency, problem formulation 2's most stable policies consistently are near 0.85 efficiency and gradually increase with little variance, meaning that closer to total potential utility values are being achieved. Problem formulation 1's policy efficiencies, in comparison, are much more scattered and do not show a clear trend. Problem Formulation 3's policy efficiencies for its most stable policies start 0.05 points lower and increase at slower increments as problem Formulation 2. Furthermore, individual PD value progressions show Egypt's PD value to stay effectively constant across the entire Euclidean distance rank order.

This indicates, in the event of full cooperation, that there may be larger utility benefits available and, specifically, that the policies that have these larger utility benefits are considered more stable. From Ethiopia's perspective, this means a higher number of policies in the stable subset that maximize utility and prevent Egypt's unbounded utility growth seen in other solution concepts. Wheeler et al. (2020) describes this period as a "new normal" period following construction and filling of the GERD when, assuming that inflows remain near the long-term average, all three nations can expect multiple benefits (mainly buffering effects) from upstream water infrastructure. However, the problem formulation suggests that high benefits can be seen if both nations are willing to engage in negotiations to initiate conditions that can lead to the "new normal", and this entails dropping their hardline stances on Nile water usage. Furthermore, **this also projects Sudan's role as a regional mediator between the two nations**. By being physically and politically in the center of conflict, Sudan poses a unique opportunity by being open to forming coalitions with all nations.

6.3.2 NUCLEOLUS'S INTERPRETATION IN THE ENB

The nucleolus's rank distribution presents an interesting inverse relationship between the rankings of the ED and those of the PI and PD. Recall that the nucleolus is designed to minimize the dissatisfaction of the least satisfied coalition in the game. Despite this, the nucleolus delivering some of the highest allocations to Egypt of any solution concept. We attributed this to Egypt's utility expectation magnitude and the Efficiency constraint. Therefore, to satisfy a low deficit from their characteristic value, the nucleolus's algorithm tries to satiate the most dissatisfied coalitions ({Sudan}, {Egypt-Sudan}, and {Sudan-Ethiopia}), which ends up resulting in even further distance between allocation values to Egypt versus those to Sudan and Ethiopia.

Appendix H.1 shows the progressions of PD values for each nation as well as the average ("total") PD value when the nucleolus is the reference solution. First, the average PD value changes only 0.2 points, which is a modest change relative to see in other solution concepts. Egypt's PD value increase 0.10 points over the course of the rankings with an acceleration at the end, attributed to boundary errors.

However, most of the continuous fall in the average PD value is caused by Ethiopia's consistently steep decrease. Consistently negative values means that the value lost to the grand coalition with a defection from Ethiopia is smaller than Ethiopia serves to lose, meaning that it looks to work together. However, this would entail that Ethiopia's allocated value is increasing as rankings become instable. Therefore, while stable Euclidean distance ranks have the most unstable PD ranks, these PD values are actually mostly negative, which still implies a net benefit for cooperation.

From the fairness index's definition, the standard deviation of the different nation's power distributions decreased as the Euclidean distance rankings become more unstable (with a fairness index range of 0.14-1.97). However, individual nation's PI values did not have nearly as dramatic of changes. Egypt's power index values eventually decreased to nearly 30 percent of its maximum value associated with the stable allocation, actually indicating a loss in power. Sudan's power index values effectively stayed within a small range until ED rank 504, after which values increased by 0.1 points (or when utility is USD 0.57 billion per year). Finally, Ethiopia's PI value slowly increased as Euclidean distance ranks become more unstable, likely attributed to the associated increase in utility. However, this increase was relatively small (0.3 points). Therefore, while it seems as if there was a large inequality associated with a high Euclidean distance rank, it is amplified and actually characterized by moderate movements in power distributions. Furthermore, this indicates that while the nucleolus treats each coalition equally, it does not look at relative distributions of utility. It fundamentally looks to satisfy those most upset with a potential allocation.

Therefore, In the ENB's case, using the nucleolus as a solution will not require large utility allocations to Sudan and Ethiopia, thus compromising an effort at finding equitable allocations. If the nucleolus is used, characteristic values with smaller differences in magnitude would aid in allocations that are closer in value. Its sensitivity to magnitude been noted as a significant general flaw in using the nucleolus (Madani and Dinar, 2013). Additionally, the nucleolus's fundamental principle is one that, in a real-life setting, may not be a unanimous goal. Therefore, while the nucleolus projects a sound solution from a theoretical standpoint, further analysis, including possible modifications to the design and parameters of the nucleolus, must be done if policymakers use this as a fair solution.

6.4 ANALYSIS LIMITATIONS

This research, despite being as extensive as possible, has certain limitations that have truncated the application of its results. This analysis was done on the output of the *ENO* model, so the limitations acknowledged by Sari (2022) are inherited by the various policy candidates and, by extension, apply to this research.

Despite game theory focusing on the strategy and perceptions from different actors, no real stakeholder input has been placed into this analysis. Information on context was synthesized through an extensive literature search and review of policy papers from analysts, many of them external to the conflict. As such, we also fall into a classic trap by using CGT, where interpreting the stability of a policy candidate (or a preference) inherently assumes a unilateral objective preference by a player agreed upon by all constituents that make up said player (Parrachino et al., 2006). This was less so for Egypt, which had two parameters that made up total utility from Nile water. But, for instance, many of the most stable policies are those that deliver severe constraints on hydropower production from Egypt's HAD. Implementing these policies will have large-scale impacts to electricity connectivity for the HAD's users, which may outweigh some of the benefits of low irrigation deficits. An ideal remedy is for ENB policymakers is to acknowledge environmental and socioeconomic considerations for a particular policy candidate before potential implementation. For the model, diversifying the objective set (by location or industry) could help with adding stakeholder voice to both analyses.

Moreover, political motivations were not considered beyond a very rudimentary interpretation based on literature and policy briefs. While the overall stances of nations were available, all stability metrics essentially looked at each nation's position (either based in physical distance or power-related) in the context of the grand coalition. As recommended by Dinar and Wolf (1997) in their stability analysis for western Middle East water allocations, the feasibility of certain policy candidates based on political barriers should also be assessed in determining stable factors. Political motivations bring a depth to assessing stability of the policies, and depending on changes in power, these motivations may rapidly change. There was no consideration of this for our analysis.

Moving to methodological limitations, we start with the development of characteristic values. There was a significant lack of clear guidelines for characteristic value calculations. Although these are formally defined as the "worth" of a coalition, the constraint of finding stability within the generated solution set post-optimization meant that characteristic values chosen needed to be compatible with the solution set's values. Specifically, for the irrigation deficit objective utility functions, major assumptions were made that led to simplifications involving the use of the water, base allocations that each nation receives, and varying reported values of crop price, crop area, and water efficiency. Simple dimensional analyses were determined to find overall water requirements for each crop. A similar problem was also faced for the WSV probability weight calculations. This error also extends to the use of density functions to determine a characteristic function. While it may provide a value that is most expected, in Egypt's case, it may have contributed to a significant undervaluation of its worth. This choice could have skewed Egypt's supposed contributions in solution concepts that incorporated Egypt's characteristic value into their calculation. Finding probability weights involves a complicated process with information, such as stakeholder perceptions and geopolitical intricacies, that could not be assessed in this study for lack of time or guidance (Wu and Whittington, 2006). To reaffirm the insights from this analysis, we could perform a sensitivity analysis using different characteristic function values to see whether similar utility and objective behaviors are obtained.

Next, as noted above, standardization of policy candidate values was performed. Despite the intentions for doing, the policies have not been optimized for efficiency of total utility. As such, we ran the risk of dampening the effects of distance between the various allocations. Also, there is a possibility that the policy outcomes are inflated by this decision. Ultimately, we recognize that using original values may produce different rankings altogether. Ranking stability using ED also may have caused neutrality in finding beneficial allocations as it deems policies unstable based on how far they are from an egalitarian allocation. Finally, considering that these policies are being considered as part of the long-term Nile Basin management, we were not able to confirm that these policies would be stable after the simulation's time frame. This is, of course, due to changing environmental conditions that will affect internal flow at various collection points, which will cause associated shifts in trade-offs and utilities. We were also not able to see how a stable policy evolves from the onset of the simulation's time frame. Addressing this and gradually assessing outcome behaviors as the simulation timeline increases could aid policymakers in seeing what factors will require changes in the stable policies implemented.

Extending the previous limitation, utility function determination is heavily simplified for this analysis. There are two options to approach this. The first option would be to retain target water volumes that each country is allocated but enhance the various elements that would use that target volume rather than simply assuming that all water is utilized towards irrigation. In other words, we should diversify the uses of available water. A second option would be to calculate utility specifically with the deficit. This also opens applications for moving water volume targets, which would reflect rising demand in downstream states. This also allows for the opportunity to incorporate diminishing marginal utility values; although, more insight would be required to understand the gradient of beneficial value.

6.5 GUIDELINES FOR FUTURE STABILITY ANALYSIS

This stability analysis, like most others, have been done in a post-optimization manner. For policymakers, performing and interpreting this process is critical (but time-consuming) for the negotiation process. Also, a different nation's perceptions of acceptable allocations, and the conflicts that result from these differences, may prove toxic to a negotiation. This has, to a certain extent, characterized the ENB's negotiation efforts thus far (Wheeler et al., 2020). While there are computational and manual components to finding a policy's stability. Basic guidelines for an analysis are provided based on insights from previous sections. We should note that prior to the incorporation into a model's optimization formulation, there are some preparations.

1. **Decision on the type of game.** Depending on the context of the conflict, each nation may suffer from incomplete information for all other nations involved. For the ENB conflict, recall that we have assumed full information knowledge from all players, considering that they are currently negotiating and understand all motivations.
2. **TU versus NTU treatment.** By using transferable utilities, we were able to look at maximizing the overall utility of a coalition. In games that allow so, policymakers can also incorporate side payments between players in TU games. With NTU games, each player would work on their own to maximize their individual benefit since a common medium of exchange (or infrastructure for an exchange) does not exist. Specific choice will depend on the context of the game.
3. **Development of utility function.** To be able to run a coalitional game, conversion of different objectives (assuming that they have varying units and directions of preference) is required. For ease, we convert them to Neumann-Morgenstern utilities so that players work to optimize these utility values in the same direction.
4. **Calculation of the characteristic values**. This is the initial attempt to understand what each possible coalition would be worth (Shapley, 1971). Depending on the stability metric used, this will also serve as a point of disagreement for a nation. That is, any utility allocation below these values would not be allowed unless an incentive is offered in the form of a common deduction ε from all players.

As noted earlier, the characteristics of most stable policies revealed a similar behavior regardless of the stability metric. This phenomenon brings positive and negative consequences. Large amounts of knowledge that emerge from having various behaviors of stable policies may interfere in *a posteriori* decision-making and engender confusion or potential conflict amongst negotiating parties (Deelstra et al., 2003) because it may cause confusion or doubt. Alternatively, a small number of options, especially those that consistently favor a specific party, may further perturb efforts for efficient negotiations, especially when incorporating a nation's perception on a fair division of a finite resource. In part, this is due to a limited option of policy selections.

In an algorithmic operationalization of a stability analysis, the Pareto set policies should meet (or approximately meet) stability thresholds that, much like simulation parameters, are adapted based on environmental and player conditions. **Stability thresholds would also be the most inclusive option with respect to finding the Pareto set.** Policies that meet these thresholds would enter the Pareto-set, as they would generate similar results.

6.5.1 *Potential Operationalization of a Stability Analysis*

Figure 6.2 shows the EMODPS schematic created by Sari (2022) with one possible approach. Note that this approach would take place within the optimization process itself. The basis of the directed policy search approach is retained. Modifications primarily arise to the policy function. For each evaluation of the policy function, we could use this function to form a "temporary utility conversion". For each nation, this would entail taking the associated objective value and converting it to a utility value via the appropriate utility function. By doing so, we can replicate the iterative nature of the policy function's evolution, only using stability metrics in addition to the performance metrics. The stability metrics, which should consider the temporary utility conversion and each nation's characteristic value, would be as used in this analysis.

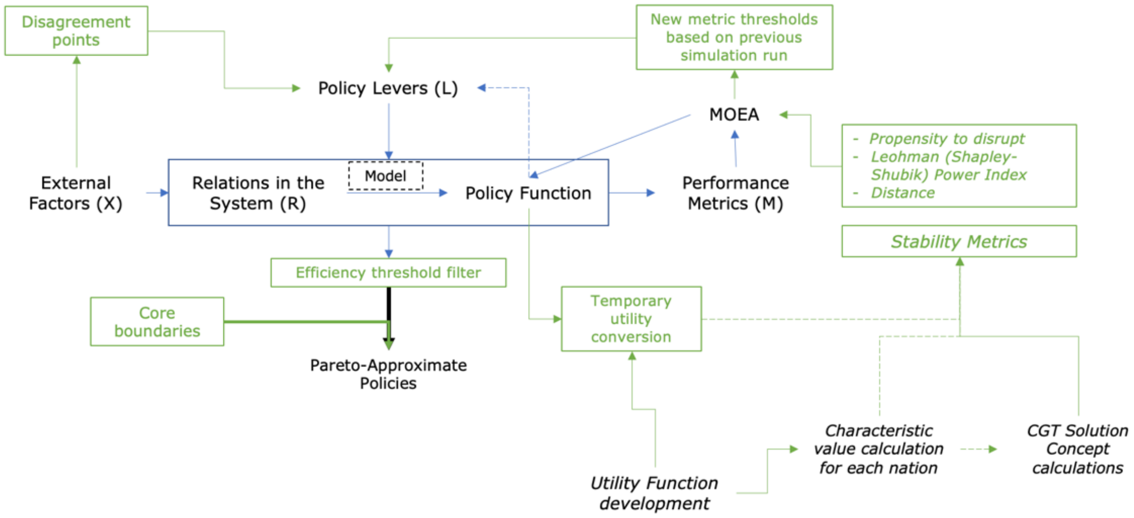


Figure 6.2: A schematic of a proposed method for incorporating a stability component into the directed policy search optimization formulation. Green arrows and boxes represent additions to the EMODPS framework schematic, originally created by Sari (2022).

After stability metrics are calculated, we should assess differences in power indices and propensities to understand power dynamics and leverage in a potential negotiation. Perhaps using the multi-objective evolutionary algorithm, we could generate new threshold values based on the results obtained from previous runs. For instance, if large power index differences were calculated through the temporary utility values, we can redefine power index thresholds to be more stringent and adhere to more equal power index values based on all previous iterations. By doing this, we attempt to address the large differences in allocations. When we redefine these thresholds, we can ultimately adjust the criteria that trigger policy levers in a way where the next functional evaluation is using policy levers that benefit a dissatisfied nation.

Finally, we should install an efficiency threshold. In the above analysis, we found that, in most rank orders, the most efficient policies were also those that had some of the lowest stability. We attempt to address this issue through this final step. Through the modification to the simulation loop, we repeatedly reconfigure the policy so that all players are satisfied. By adding an efficiency filter, predefined with a threshold, we filter those already stable policies that have the highest total utility associated with them. Furthermore, we would check a policy's location in the Core or the minimum ε-value required. At this stage, manual analysis on the various policies in the Pareto set should be conducted. This is where, by analysts or policymakers evaluating these options, political considerations have an opportunity to enter the stability analysis process.

6.5.2 CHANGES TO THE OPTIMIZATION FORMULATION

A significant improvement to water allocation models would be to incorporate policies that are highly stable among all the involved players in addition to other objectives. This would involve directly incorporating stability and policy efficiency criteria into the optimization formulation prior to creating the Pareto set. In the case of ENB, several changes would be required. The current optimization formulation in the ENO model is developed solely to maximize the benefits of each nation's respective objectives. One potential change is to expand the current objective space to include a cumulative stability objective for each nation. Similar to the design in Section 6.5.1, stability metrics would be incorporated as system relationships to optimize specific objectives, rather than keeping them solely as metrics assessed after each iteration. The model's system relationships would also be modified to include stability objective values (from the previous run) as a parameter for determining the release decisions. As noted earlier, stability is a characterization of a policy, and thus, multiple stability metrics would be included.

A nation's satisfaction with the allocation observed in a particular iteration would be determined by measuring its distance from a pre-defined disagreement point, which may be its characteristic value. If a nation's stability objective value is higher than others, this would trigger release decisions that would benefit dissatisfied nations more until an equitable stability value is achieved. Additionally, the Loehman power index could be used to find optimal stability values, with weighting for a priority scheme that determines the dominant stability metric for a nation. For instance, if Egypt continues to experience moderate droughts with each possible allocation, they may opt to assign a higher priority to distance from their respective disagreement point.

To promote high policy efficiency, stability metrics could be made co-dependent. Theoretically, this would mean that optimal stability values could be achieved through increasing total utility values for policy iterations that maximize other objectives. Ultimately, policies with high stability objectives can be identified for each nation, and policymakers can engage in negotiations using a subset of equally stable policy candidates that do not require high efficiency sacrifices.

An alternative strategy for improving water allocation models involves the use of a bankruptcy game model. This method was inspired by Mianabadi et al. (2015), who employed the bankruptcy game model to resolve water allocation conflicts in the Tigris River basin involving Turkey, Syria, and Iraq. The ENO model reveals that demand exceeds supply in the Nile River basin, as indicated by the irrigation deficits of Sudan and Egypt. Such a situation is common in transboundary water conflicts. In conflict resolution, bankruptcy theory is a widely used tool in the context of Cooperative Game Theory (CGT) assessments. It is utilized to redistribute assets when they are inadequate to meet the claims of all stakeholders involved.

The proposed bankruptcy game model translates each nation's objectives into damages or costs that must be minimized, while the stability objectives remain the same as before and must be maximized. In each iteration, the total Nile River flow deficit is divided among the nations, and the divisions are updated based on the stability objectives. The policies that meet the Pareto-optimal criterion are those that strive to distribute damage due to water scarcity equitably. Nonetheless, the successful design of the bankruptcy game model requires riparian bargaining weights to be assigned to each nation based on their contributions to the water source and leverage in negotiations. For downstream states in the ENB, this could pose a significant challenge (Degefu et al., 2018). Further research is required to overcome this challenge and refine the model.

The adoption of the bankruptcy game model has the potential to benefit policymakers by helping to mitigate risks associated with water scarcity. This approach broadens the focus of conflict resolution beyond maximizing water benefits that may not be available in the future. Rather, it aims to achieve a fair distribution of the available water resources among the riparian nations.

7. CONCLUSION

7.1. ANSWERS TO RESEARCH QUESTIONS

The main research question for this research was *"How can the stability of different Pareto-front policy candidates be relatively assessed in the case of the ENB?".* The intent with this question was two-fold. First, it was to assess stability policies that were generated through the EMODPS framework for decision-making for multi-objective, multi-stakeholder problems. Second, we hoped to contribute to methodological studies by conducting a relative stability analysis to determine changes in objective trade-offs and utility distribution behaviors, thereby assessing policy candidates against each other.

Stability is an overarching characterizing term that can be determined through various concepts. Assessing dissatisfaction from individual and group coalitions are important to understand inequalities in policy candidates. This is with the assumption that higher inequalities will imply lower acceptability for all players. Alternatively, the power dynamics between players are also important to consider for each strategy in coalitional settings. When we consider both aspects, we theoretically can identify which policies (or policy behaviors) are optimum for long-term cooperation. To accomplish this, we designed an analysis where various solution concepts from cooperative game theory are calculated, each forming a unique solution to the game. For each solution concept, stability will be assessed through the use of three stability metrics that fulfill the above observations. We conducted this analysis on a Pareto set of policies to characterize the most stable policies in the set. We focus the study on a water allocation conflict in the Eastern Nile Basin using a simulation model's output as the policy set of interest.

(a) What are different concepts of stability that can be applied in cooperative game theory, and what are the assumptions and characteristics of each concept?

One stability metric is Euclidean distance, which is the distance between a policy candidate and a focal point (in our case, one of the CGT solution concepts). Euclidean distance is the simplest of the stability metrics used for this analysis. Euclidean distance functions with the assumption that the greater the distance between a reference point and a nation's allocation, the greater the dissatisfaction to the player, thereby reducing stability. However, when we assume the efficiency of solutions (meaning that the grand coalition must allocate its entire worth), larger advantages of utility to one player will cause dissatisfactions to other players, and therefore these solutions will also be deemed less stable as the magnitude of advantage increases.

The second stability metric is the Loehman Power Index, which is a modification of the Shapley-Shubik power index. The Loehman Power Index is the extension to coalitional games and is the ratio of an individual player's payoff to the total payoff of all members of the grand coalition. However, the stability of a solution is determined through a fairness index, which is the coefficient of variation amongst all the power indices. The Power Index, unlike Euclidean distance, does not vary by solution concept; instead, it is a unique calculation for each specific policy candidate. The Power Index provides an indication on the power dynamics within the grand coalition, assuming that power is directly correlated with allocation value. More equitable values are desired for the most stable policies. Thus, for the fairness index, higher values signify greater inequalities in power between players, thereby making the policy less stable.

Finally, the propensity to disrupt is the final concept used in this analysis. It is defined as the ratio of expected loss from all other players in a coalition if a specific player defects from an allocation to the expected loss for the player themselves. Lower (negative) propensity to disrupts indicate a desire to cooperate, since the loss to the player is greater than that of the coalition. More unstable policies are associated with higher propensity values, where the player will not lose nearly as much as the coalition in the event of their defection. Propensities to disrupt also are proxies for estimating the negotiation power that a nation has in the grand coalition. Greater negotiation power for a nation would indicate they are able to obtain higher benefits to the deficit of other players.

(b) How do distributional outcomes and trade-offs experienced by ENB stakeholders differ between the baseline optimization and different solution concepts and stability metrics?

The baseline analysis simply placed each nation's characteristic values as the solution. As in the *ENO* model, trade-offs were witnessed between Ethiopia's hydropower production levels the irrigation deficit values for Egypt and Sudan. The most stable policies, across all stability metrics, favored high Ethiopian utility in exchange for high irrigation demand deficits for Sudan and moderate levels (approximately 10 BCM per year) for Egypt. Egypt's HAD low-water level frequency objective is almost always optimized in the baseline analysis's stable policies. The HAD is a regulation tool for irrigation spill in Egypt, so as a higher deficit emerges, this would entail higher HAD water levels which allow it to produce hydropower. Egypt's HAD and irrigation objectives are seen as internal prioritization conflicts for Egypt. Unstable policies showed differing patterns but mostly showed preference towards maximizing Egypt's utility allocation through very low irrigation deficit values to the detriment of Ethiopian utility.

In all solution concepts barring the nucleolus, allocations and power indices between Egypt and Ethiopia/Sudan diverged as policies became less stable. Propensities to disrupt converged, signifying a leverage shift in favor of Ethiopia and Sudan at unstable policy ranks. The symmetric Shapley Value showed similar dynamics to the baseline analysis, with distinct changes really only being seen in the ranges of utilities for the most stable policies. When probability weights of different coalitions were changed (to full cooperation), objective trade-offs remained similar. Observations showed that problem formulation that placed Ethiopia in a non-cooperative setting significantly detracted their allocations in the most stable policies, while this punishment is not nearly as severe when applied to a non-cooperative Egypt. Symmetric Nash-Harsanyi solutions produced similar behaviors, and Egypt's "runaway" utility behavior in unstable policies was confirmed in Scenario 1 with asymmetric bargaining weights favored for Egypt. Finally, the nucleolus's solution was the complete opposite as previous solution concepts. Stable policies significantly favored Egypt while minimizing Ethiopian utility. This was attributed to the nucleolus's goal of satisfying the most dissatisfied coalitions with respect to their characteristic value; however, magnitude differences between Egypt and other nations meant very small allocation shifts needed to satisfy the most dissatisfied nations (those primarily with upstream states), thereby allocating even more to Egypt.

(c) How can the results from the stability analysis on the ENB inform the enhancement of an optimization formulation to include stability as an optimizing objective from the onset?

The formation of characteristic values for all coalitions and utility function definitions should be the first steps taken. Each solution concept employs a different theory of fairness which governs their calculations. Each stability metric defines stability using a different set of assumptions. If we assume that a truly stable policy is one that is optimized on all fronts, we can use these metrics in conjunction with the performance metrics that are already used in ENO model. Also, to generate policies in the Pareto-set that are already optimized for stability, we should define adaptive stability thresholds. These thresholds, similar to the simulation's free parameters, would change based on past allocations in order to achieve a stable allocation through multiple functional evaluations of the simulation.

Finally, one of the significant insights from our analysis was that policy candidates that ranked most stable for most stability metrics were among the least efficient, meaning that they did not achieve full potential utility based on the grand coalition's characteristic value. After optimization of the three stability metrics, a threshold should be used to filter through policies that achieve a high efficiency value. When trying to change the optimization problem itself, two potential options would be to expand the objective set to include individual aggregated stability objectives for all players. These objectives, which should be maximized would be co-dependent on each other. Furthermore, this co-dependency can result in higher efficiency because of the interests of maximizing benefit from other objectives. The second option would be to change the formulation from a utility maximization to a cost-sharing game by restructuring the optimization as a bankruptcy game. Stability objectives could still be incorporated, and stable policies would be ones where the costs of decreases in Nile river volume are equitably distributed.

7.2 POLICY RECOMMENDATIONS

There is significant concern with the ongoing stalemate in negotiations between all three nations. Despite multiple rounds of failed negotiations, Ethiopian officials went ahead to start filling the GERD reservoir in spite of running the risk of exacerbated future tensions with its downstream neighbors. Egypt and Ethiopia's aversion to one another are evident in their robust trade-offs. The results from the stability analysis seem to indicate that, with most solution concepts, prioritizing Ethiopian hydropower production is the most stable option. This is one of the limitations of the stability analysis, in that it does not consider geopolitical context in its decision. Obviously, this type of policy does not bode well in implementation. Egypt has repeatedly resisted any attempts to pass any agreements that advocate for high filling durations in Ethiopia. Likewise, policies that Egypt would consider are those where differences in utilities are so great that both other nations simply will never agree to such an allocation.

Instead, **a pragmatic solution for the ENB would be to look at strategies that require utility compromises on part of all nations**, similar to what is observed with the near-most stable ranks from the symmetric Shapley Value. This would have several benefits. Trade-offs are most prominent between the Egypt's irrigation demand deficits and HAD low-water level frequencies when they are trying to maximize their overall benefit. Due to growing water demand, Egypt's dwarfing of HAD production capacity will increase if it maintains its stance on wanting to secure enough water for agriculture. There are several policies ranked highly stable to try to relax this trade-off, which will enhance total benefits from both to Egypt. By relaxing their internal trade-off between hydropower and irrigation, Egypt will risk increasing evaporative losses due to higher HAD levels. However, by advocating for these policies, it also fosters a welcome cooperative strategy which could amount to a compensation for lost water in the future. Furthermore, these policies produce utilities close to Ethiopian maximum but do not allow it to operate at maximum levels. Because of the high allocations to Egypt, this is one of the few instances where their willingness to cooperate overlaps with policies that give a relatively high power to Ethiopia and Sudan. Compromise policies also have total policy efficiency levels that hover between 0.8-0.85, meaning a relatively low loss of efficiency for stability. By leveraging this rare alignment, this is the small subset of policies that seem to be the most promising for all nations. Specific policies that could show this can be some "Best Egypt HAD" policies (Table H.3 in Appendix). Specifically, policy numbers 96, 149, and 253 showcase characteristics of compromise policies. They consistently have high individual and total efficiency values between 0.8-0.92 along with high stability ranks across most solution concepts (barring the nucleolus) and stability metrics. Their specific power indices and PD values indicate smaller differences in gains from utilities. Furthermore, Egypt's individual PD value hovers between 0.01-0.03, which indicates a positive but relatively weak propensity to disrupt. Combined with Sudan and Ethiopia's negative PD values, it indicates that these strategies have a strong possibility of sustaining coalitional agreements.

7.3 EXTENSIONS AND FUTURE RESEARCH

Suggestions here are partially based on the limitations that this analysis had. Future research could start with accounting for the lack of stakeholder involvement in this analysis. To be truly stable, research on the socioeconomic and environmental effects of such stable policies could be explored. An immediate extension to this would be to follow the second part of Sari (2022)'s workflow and re-simulate the model using the identified stable policies to see the overall effects.

Furthermore, this stability analysis method could easily be used in other regions with water conflicts. This would be for an exploration on how geographic constraints could change results. Furthermore, an interesting extension would be to use a relative stability analysis in identifying a set of adaptive policies. This would be in accordance with the dynamic adaptive policy pathways (DAPP) framework, where a policy change is triggered based on environmental or regulatory conditions (Haasnoot et al., 2013). By combining a stability analysis with DAPP decision-making framework, one could identify vulnerabilities in the hydrological system and aid policymakers in forming the set of policies that, while adaptive, are also robust in their creation. Seeing that finding tipping points for policy transition are also a point of research, identifying objective and utility behaviors may also assist in determining important factors to determine tipping points from.

Another interesting extension of this stability analysis could be identifying evolutionary stable strategies for the ENB conflict. These are strategies that, when implemented in a population, are not defeated nor replaced by another strategy through natural gravitation to this new strategy (Axelrod, 1988). Evolutionary models and evolutionary stable strategies have been used previously; however, no studies have been done specifically on river allocations, and research in this field is still relatively novel. By employing evolutionary stable strategies and combining a search for said strategies through optimization formula, this can potentially be used to identify robust strategies in even more complicated models.

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APPENDIX

A. UTILITY FUNCTION PARAMETERS

1. COST PARAMETERS (EGYPT)

Parameter	Parameter Notation	Current Parameter Value (USD/kg)	Source
Cost, barley	C_{bar}	0.2800	UN, FAOSTAT (2022)
Cost, corn	C_{cr}	0.3896	UN, FAOSTAT (2022)
Cost, cotton	C_{ct}	0.2829	UN, FAOSTAT (2022)
Cost, groundnuts	C_{gn}	4.5242	UN, FAOSTAT (2022)
Cost, soybeans	C_{sb}	0.3486	UN, FAOSTAT (2022)
Cost, sorghum	C_{sg}	0.1823	UN, FAOSTAT (2022)
Cost, wheat	C_{w}	0.4202	UN, FAOSTAT (2022)
Cost, rice	C_{r}	0.2204	UN, FAOSTAT (2022)

C_{Egypt} = *{Barley, Corn, Cotton, Groundnuts, Soybeans, Sorghum, Wheat, Rice}*

2. COST PARAMETERS (SUDAN)

Parameter	Parameter Notation	Current Parameter Value (USD/kg)	Source
Cost, cotton	$C_{bar,S}$	0.6173	UN, FAOSTAT (2022)
Cost, groundnuts	$C_{cr,S}$	0.6465	UN, FAOSTAT (2022)
Cost, wheat	$C_{ct,S}$	0.7781	UN, FAOSTAT (2022)
Cost, sorghum	$C_{gn,S}$	0.5646	UN, FAOSTAT (2022)

C_{Sudan} = *{Cotton, Groundnuts, Sorghum, Wheat}*

3. WATER EFFICIENCY PARAMETERS (EGYPT)

Parameter	Parameter Notation	Current Parameter Value (m^3/m^2)	Source
Water efficiency, barley	WU_{bar}	0.4857	Mahmoud & El-Bably, 2017
Water efficiency, corn	WU_{cr}	0.9081	Mahmoud & El-Bably, 2017
Water efficiency, cotton	WU_{ct}	1.3312	Mahmoud & El-Bably, 2017
Water efficiency, groundnuts	WU_{gn}	0.9679	Mahmoud & El-Bably, 2017
Water efficiency, soybeans	WU_{sb}	1.0083	Mahmoud & El-Bably, 2017
Water efficiency, sorghum	WU_{sg}	0.9410	Mahmoud & El-Bably, 2017
Water efficiency, wheat	WU_{w}	0.6493	Mahmoud & El-Bably, 2017
Water efficiency, rice	WU_{r}	1.2381	Mahmoud & El-Bably, 2017

4. WATER EFFICIENCY PARAMETERS (SUDAN)

Parameter	Parameter Notation	Current Parameter Value (m^3/m^2)	Source
Water efficiency, cotton	$WU_{bar,S}$	0.6200	Widaa et al. (2011); Satti et al. (2015)
Water efficiency, groundnuts	$WU_{cr,S}$	1.0200	Widaa et al. (2011); Satti et al. (2015)
Water efficiency, wheat	$WU_{ct,S}$	0.3555	Widaa et al. (2011); Satti et al. (2015)
Water efficiency, sorghum	$WU_{gn,S}$	0.8150	Widaa et al. (2011); Satti et al. (2015)

5. YIELD PARAMETERS (EGYPT)

Parameter	Parameter Notation	Current Parameter Value (kg/m^2)	Source
Yield, barley	Y_{bar}	0.1179	US Dept. of Agr (2022)
Yield, corn	Y_{cr}	0.7257	US Dept. of Agr (2022)
Yield, cotton	Y_{ct}	0.0714	US Dept. of Agr (2022)
Yield, groundnuts	Y_{gn}	0.2902	US Dept. of Agr (2022)
Yield, soybeans	Y_{sb}	0.2540	US Dept. of Agr (2022)
Yield, sorghum	Y_{sg}	0.4627	US Dept. of Agr (2022)
Yield, wheat	Y_{w}	0.5806	US Dept. of Agr (2022)
Yield, rice	Y_{r}	0.7620	US Dept. of Agr (2022)

6. Yield Parameters (Sudan)

Parameter	Parameter Notation	Current Parameter Value (kg/m²)	Source
Yield, cotton	$Y_{bar,S}$	0.0569	US Dept. of Agr (2022)
Yield, groundnuts	$Y_{cr,S}$	0.0725	US Dept. of Agr (2022)
Yield, wheat	$Y_{ct,S}$	0.2177	US Dept. of Agr (2022)
Yield, sorghum	$Y_{gn,S}$	0.0544	US Dept. of Agr (2022)

7. Area Parameters (Egypt)

Parameter	Parameter Notation	Current Parameter Value (1000 ha)	Source
Area, barley	A_{bar}	83	US Dept. of Agr (2022)
Area, corn	A_{cr}	836	US Dept. of Agr (2022)
Area, cotton	A_{ct}	96	US Dept. of Agr (2022)
Area, groundnuts	A_{gn}	64	US Dept. of Agr (2022)
Area, soybeans	A_{sb}	9	US Dept. of Agr (2022)
Area, sorghum	A_{sg}	151	US Dept. of Agr (2022)
Area, wheat	A_{w}	1360	US Dept. of Agr (2022)
Area, rice	A_{r}	637	US Dept. of Agr (2022)

8. Area Parameters (Sudan)

Parameter	Parameter Notation	Current Parameter Value (1000 ha)	Source
Area, cotton	$A_{bar,S}$	192	US Dept. of Agr (2022)
Area, groundnuts	$A_{cr,S}$	3109	US Dept. of Agr (2022)
Area, wheat	$A_{ct,S}$	269	US Dept. of Agr (2022)
Area, sorghum	$A_{gn,S}$	7460	US Dept. of Agr (2022)

9. Water Ratio Parameters (Egypt)

Parameter	Parameter Notation	Current Parameter Value	Source
Water ratio, barley	rat_{bar}	0.0143	US Dept. of Agr (2022)
Water ratio, corn	rat_{cr}	0.2699	US Dept. of Agr (2022)
Water ratio, cotton	rat_{ct}	0.0454	US Dept. of Agr (2022)
Water ratio, groundnuts	rat_{gn}	0.02202	US Dept. of Agr (2022)
Water ratio, soybeans	rat_{sb}	0.0032	US Dept. of Agr (2022)
Water ratio, sorghum	rat_{sg}	0.0505	US Dept. of Agr (2022)
Water ratio, wheat	rat_{w}	0.3140	US Dept. of Agr (2022)
Water ratio, rice	rat_{r}	0.2805	US Dept. of Agr (2022)

10. Water Ratio Parameters (Sudan)

Parameter	Parameter Notation	urrent Parameter alue	ource
Water ratio, cotton	$rat_{bar,S}$	0.0125	US Dept. of Agr (2022)
Water ratio, groundnuts	$rat_{cr,S}$	0.3350	US Dept. of Agr (2022)
Water ratio, wheat	$rat_{ct,S}$	0.0101	US Dept. of Agr (2022)
Water ratio, sorghum	$rat_{gn,S}$	0.6423	US Dept. of Agr (2022)

11. HAD Income Parameters (Egypt)

Parameter	Parameter Notation	Current Parameter Value	Units	Source
HAD Base hydropower production Level	$BAHP_{HAD}$	10000	GWh	KfW Entwicklungsbank (Analysis) (2016)
Cost, HAD Hydropower	C_{HP}	0.10	USD/kWh	Hussein et al., 2016

12. GERD Income Parameters (Ethiopia)

Parameter	Parameter Notation	Current Parameter Value	Units	Source
Export Percentage	pc_{ex}	0.10	n/a	Endale (2022)
Domestic Percentage	pc_{do}	0.90	n/a	Endale (2022)
Export Price	$P_{HP,ex}$	0.10	USD/kWh	Basheer et al. (2021)
Domestic Price	$P_{HP,dom}$	0.05	USD/kWh	Estimation based on local news

B. Characteristic Values: Individual Utility Distributions

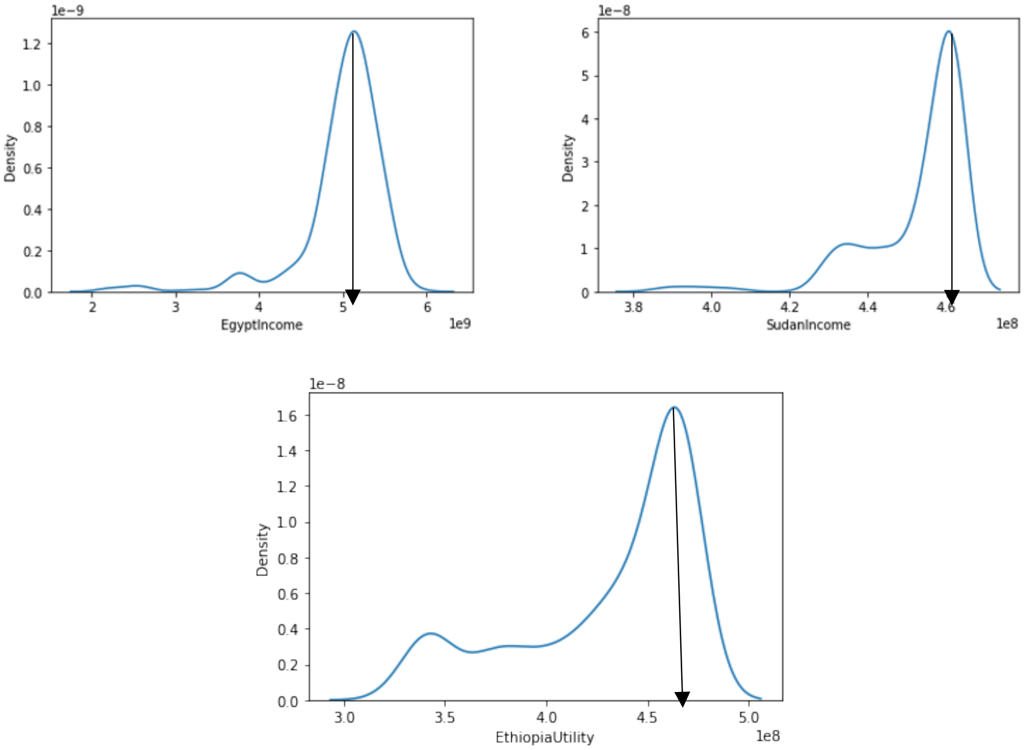
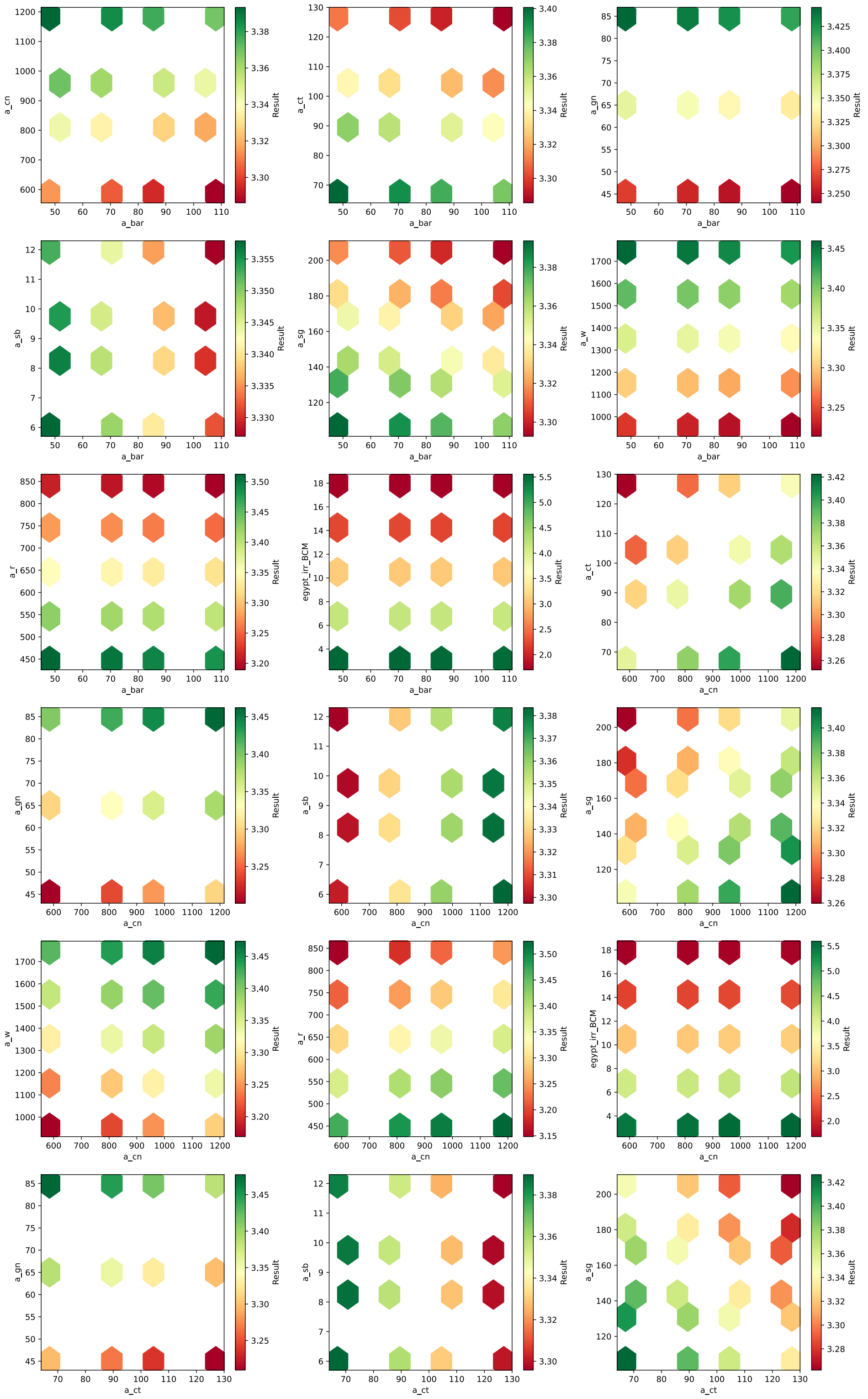
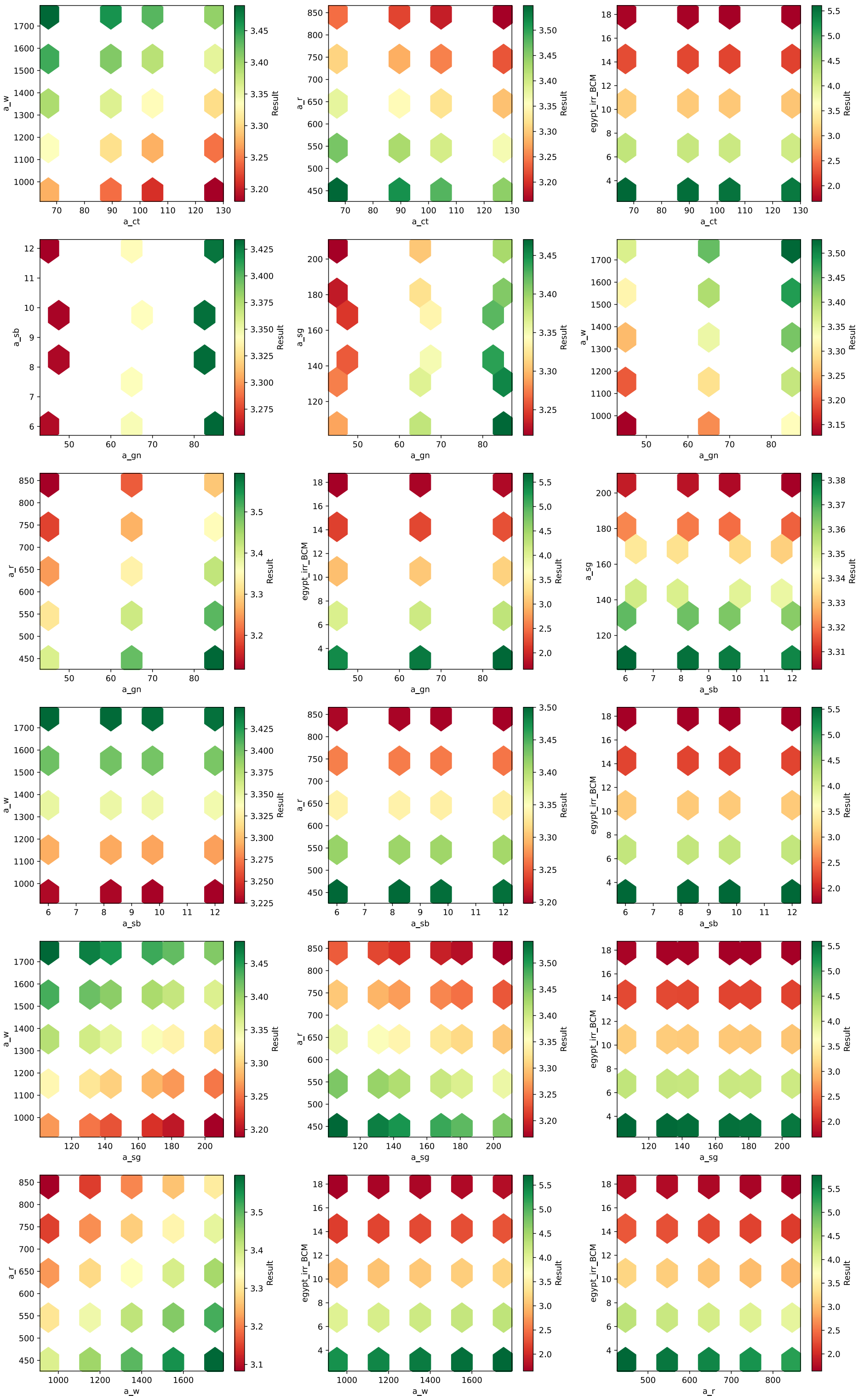


Figure B: The density distributions of the various utility values for each nation in each policy candidate. Characteristic values were determined for each individual nation by assuming the value with the highest density, indicating the highest likelihood of expected utility amongst all policies. Income or Utility values are in [USD billion per year].

C. UTILITY FUNCTION SENSITIVITY ANALYSIS

1. *AREA VARIATION: UTILITY FROM EGYPT IRRIGATION DEMAND DEFICIT*

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1400
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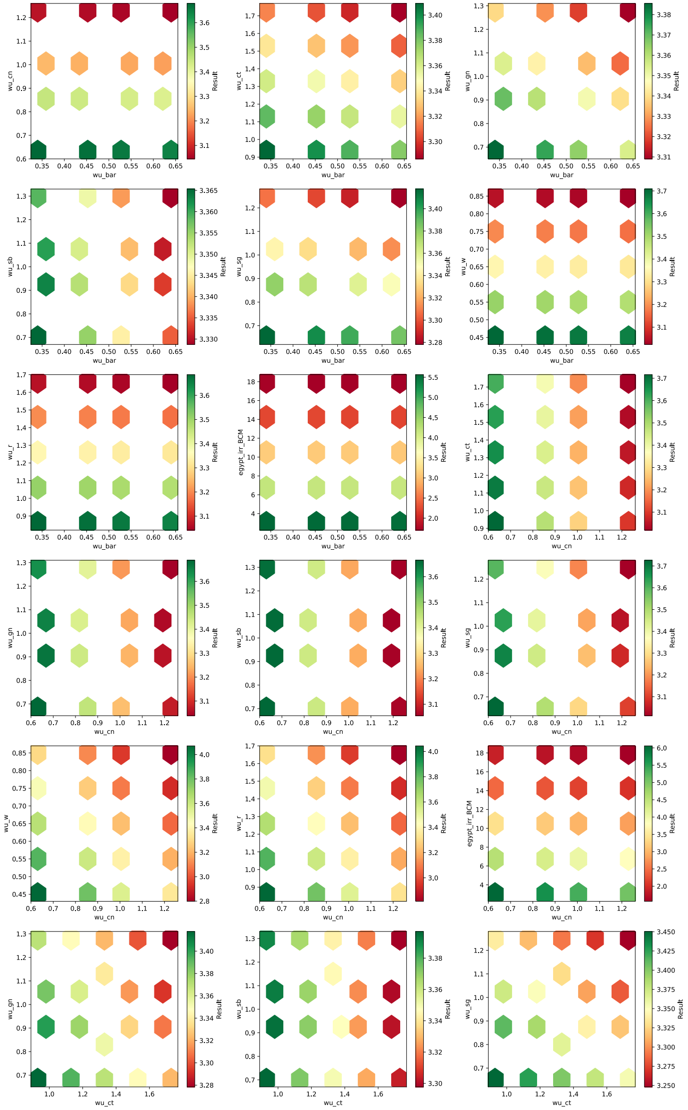
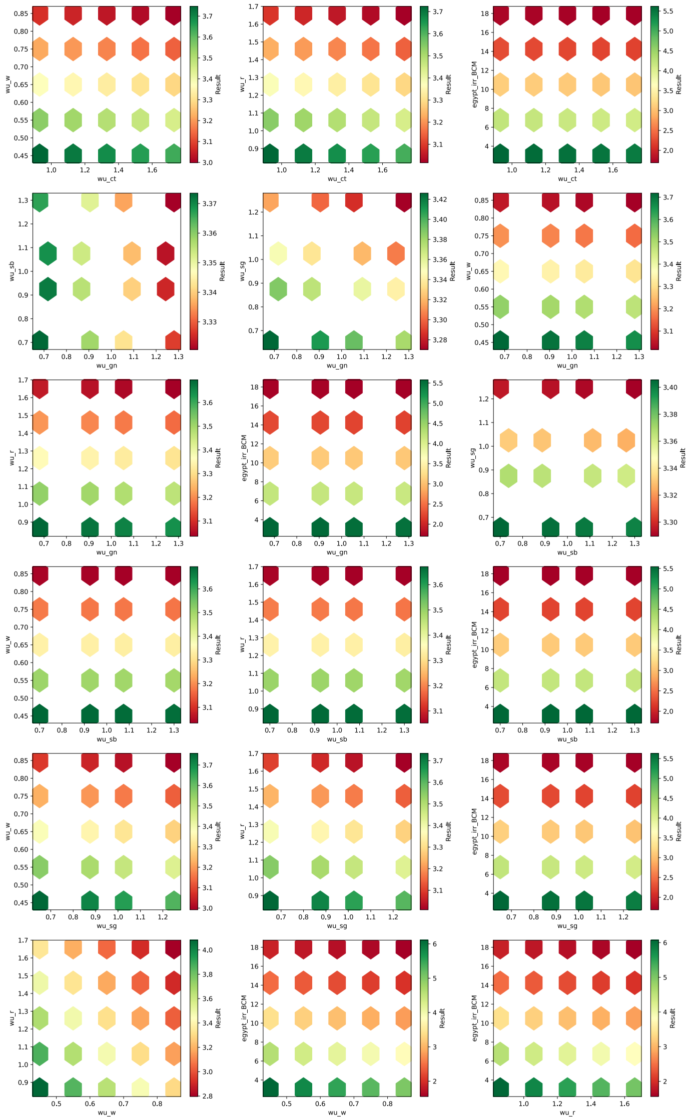
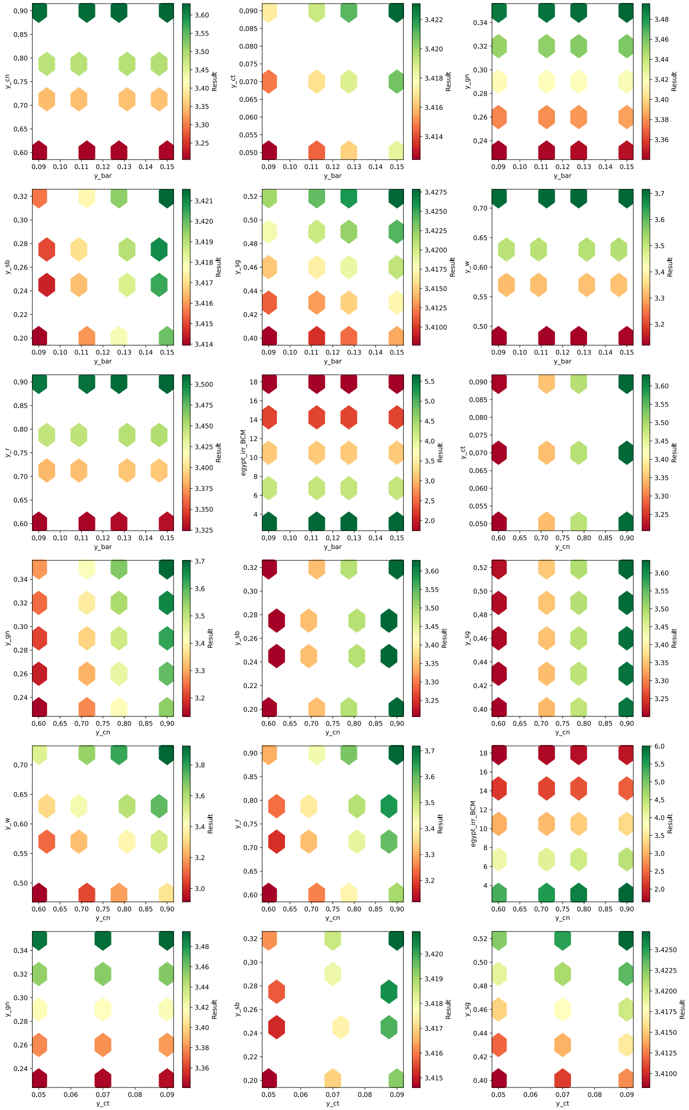
130
Result
3.20
3.25
3.30
3.35
3.40
3.45
a_r
450
500
550
600
650
700
750
800
850
3.50
egypt_irr_BCM
4
6
8
10
12
14
16
18
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
a_sb
6
7
8
9
10
11
12
a_gn
50
60
70
80
3.275
3.300
3.325
3.350
3.375
3.400
3.425
a_sg
120
140
160
180
200
3.15
3.1
3.2
3.3
3.4
3.5
3.31
3.32
3.33
3.34
3.35
3.36
3.37
3.38
3.225
3.250
a_w
1000
1200
1400
1600
a_r
500
600
700
800

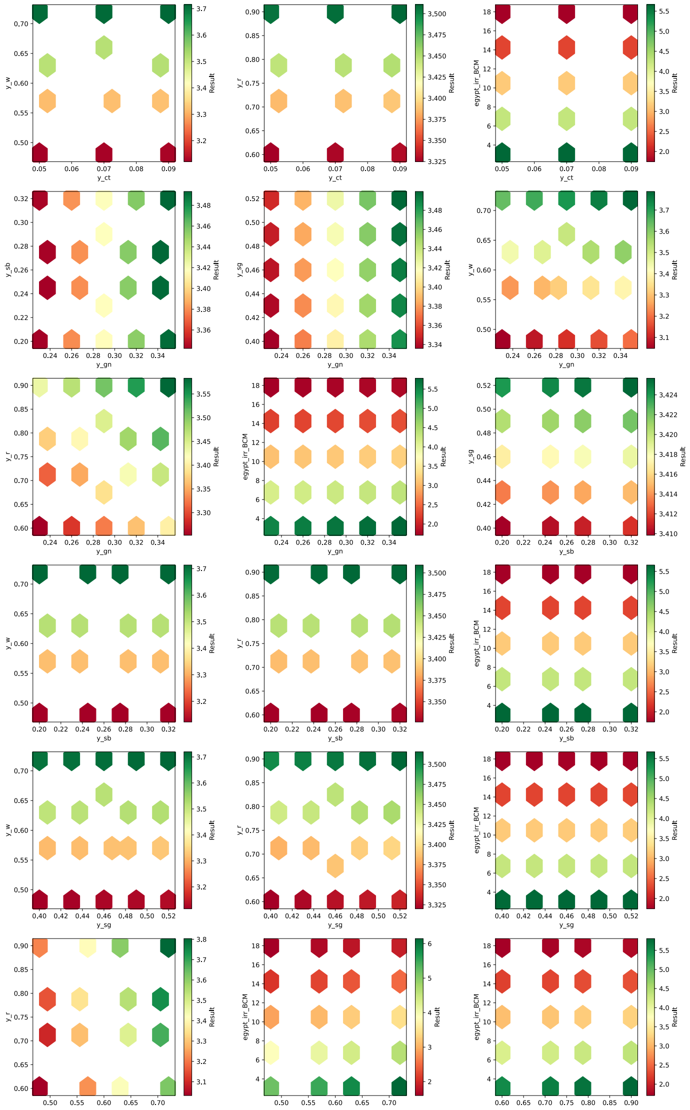
2. WATER USE VARIATION: UTILITY FROM EGYPT IRRIGATION DEMAND DEFICIT



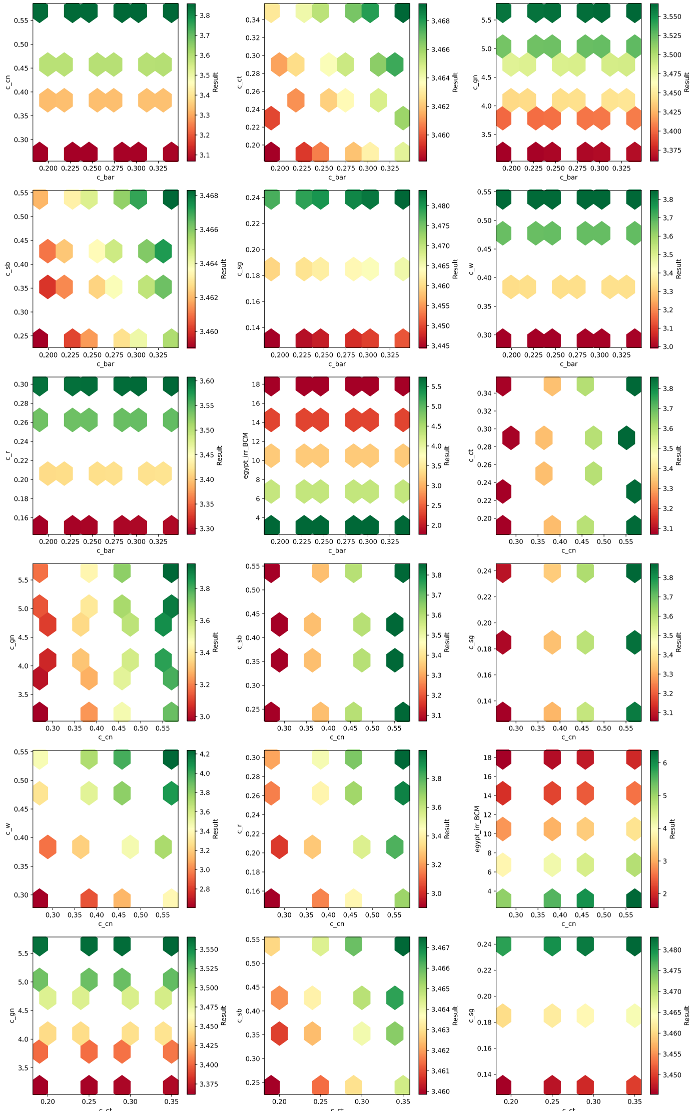


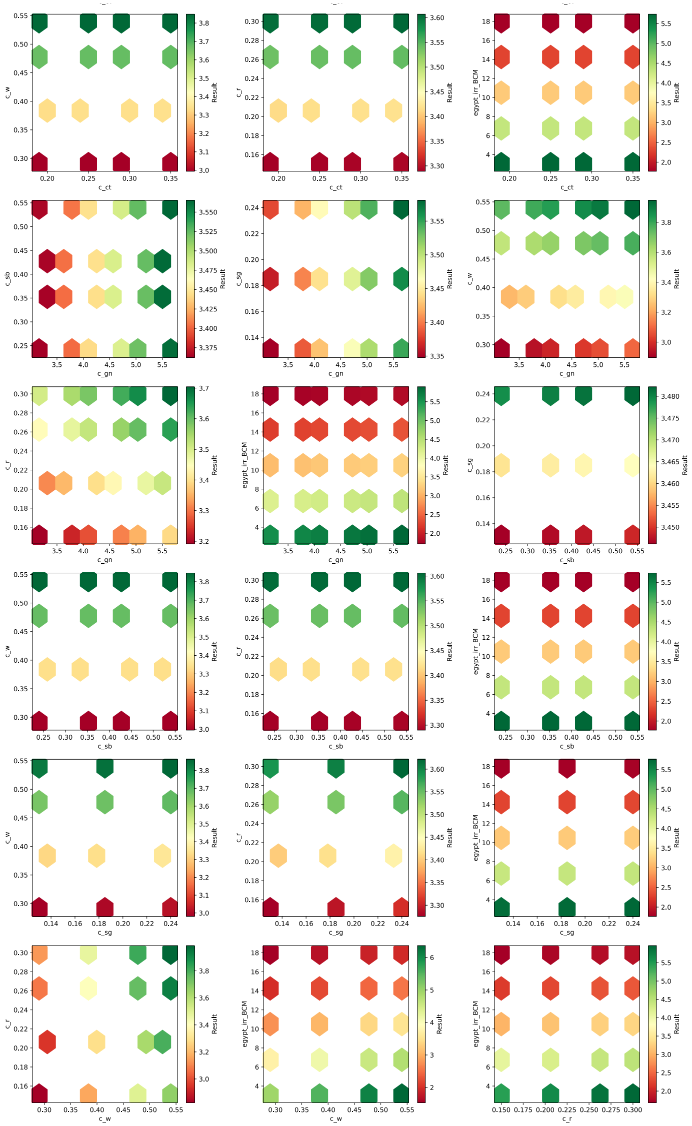
3. YIELD VARIATION: UTILITY FROM EGYPT IRRIGATION DEMAND DEFICIT



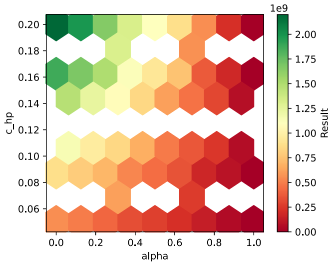


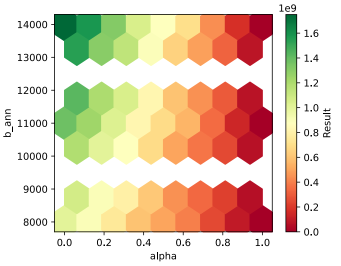
4. COST VARIATION: UTILITY FROM EGYPT IRRIGATION DEMAND DEFICIT

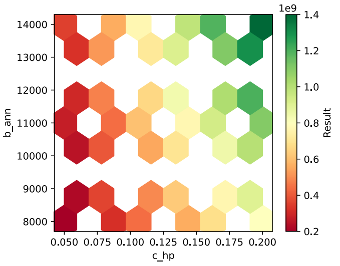




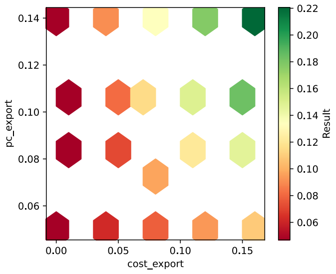
5. Utility from Egypt HAD Minimum Power Generation Level

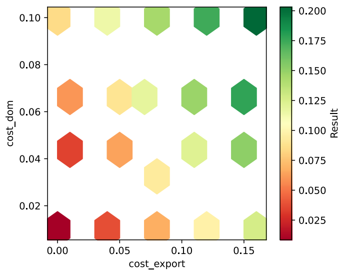


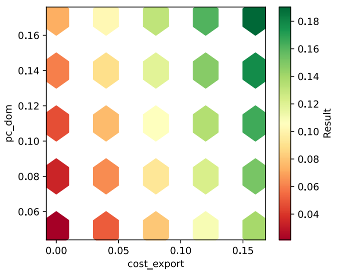


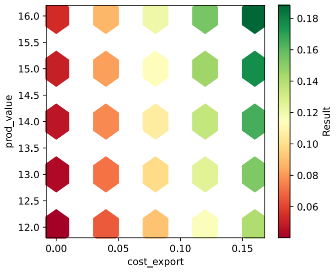


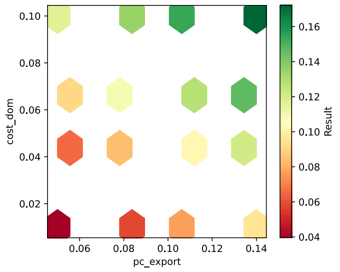
6. Utility from Ethiopia's Hydropower Production from GERD

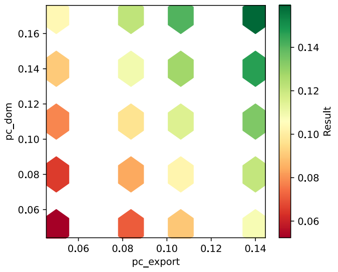


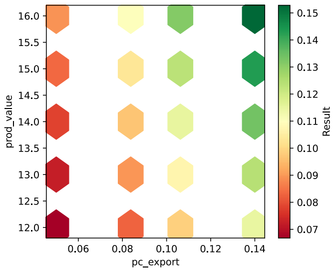


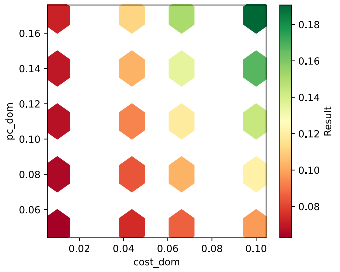


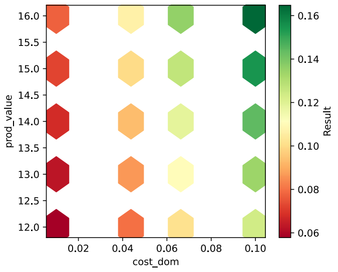


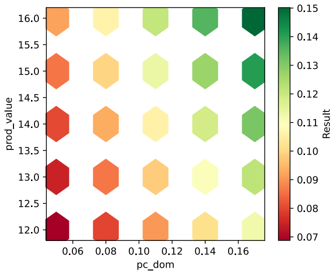




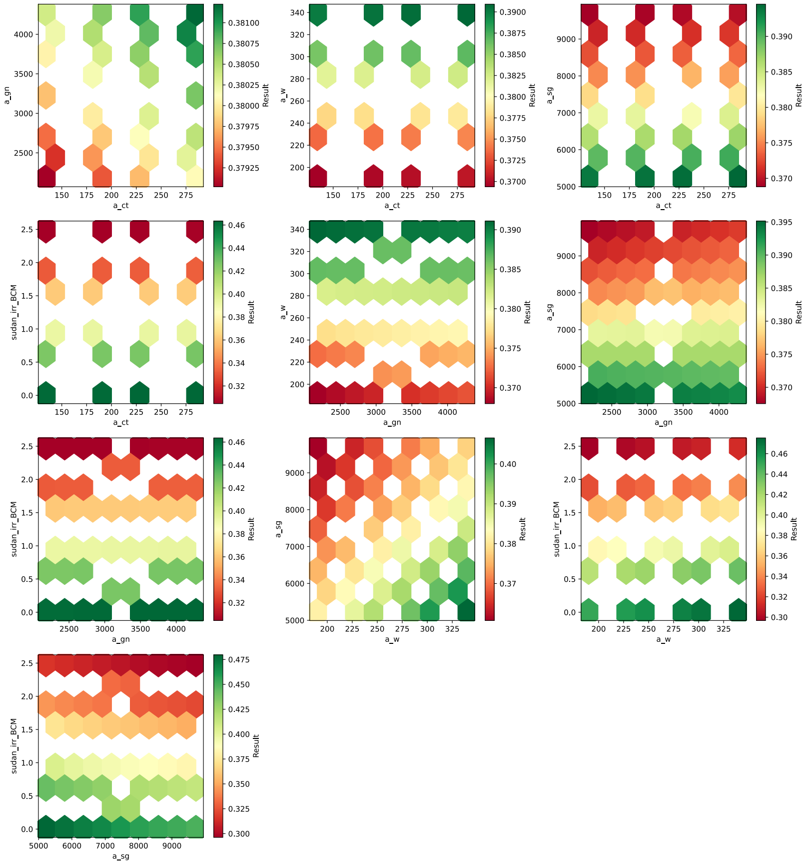




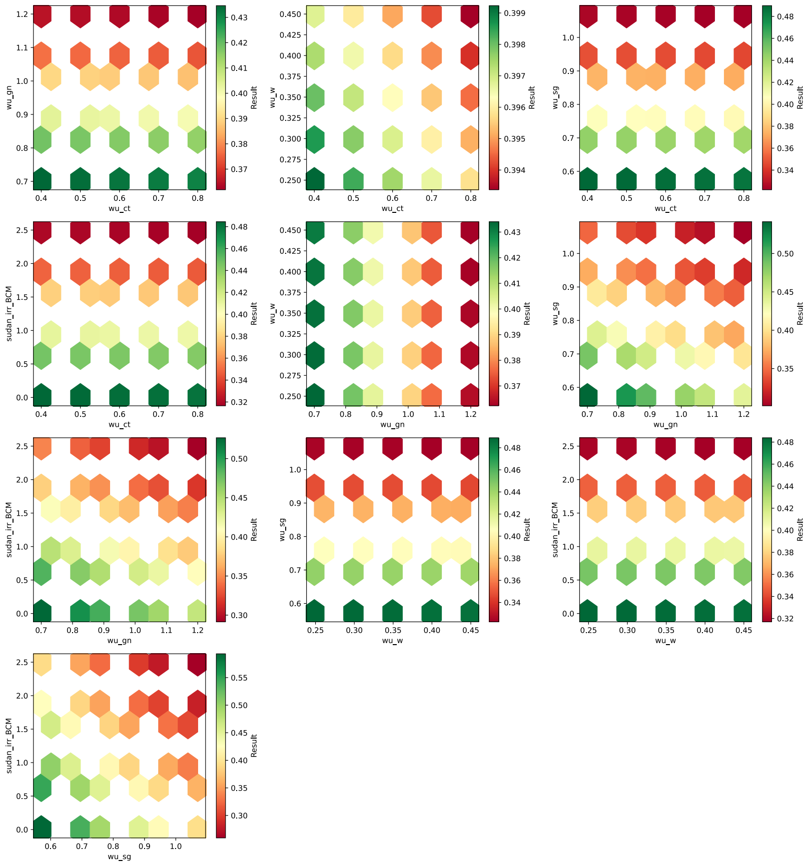




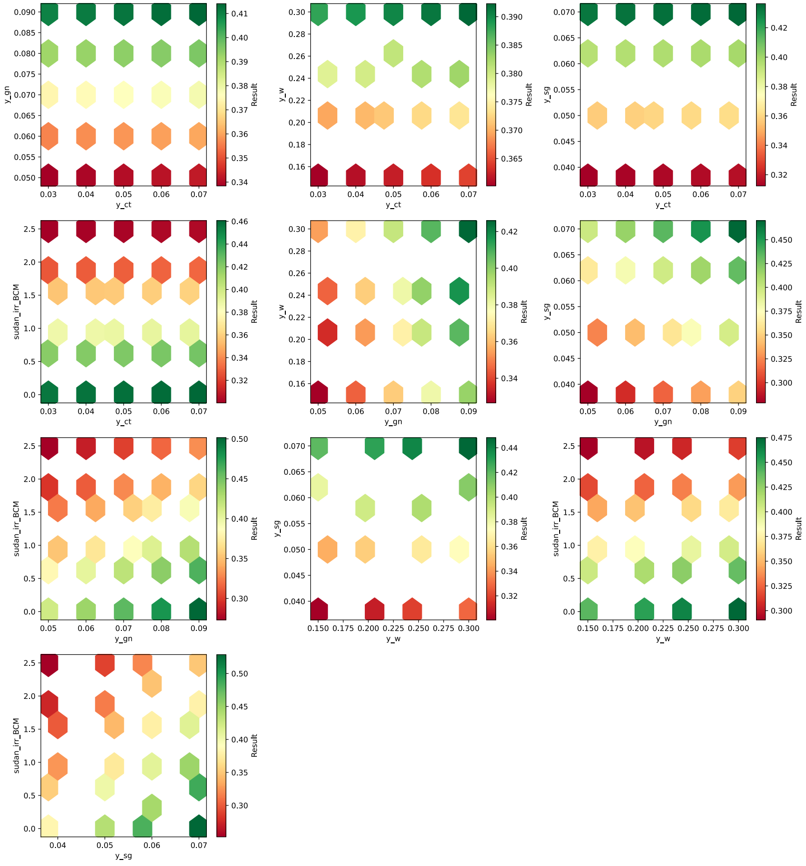
7. AREA VARIATION: UTILITY FROM SUDAN IRRIGATION DEMAND DEFICIT



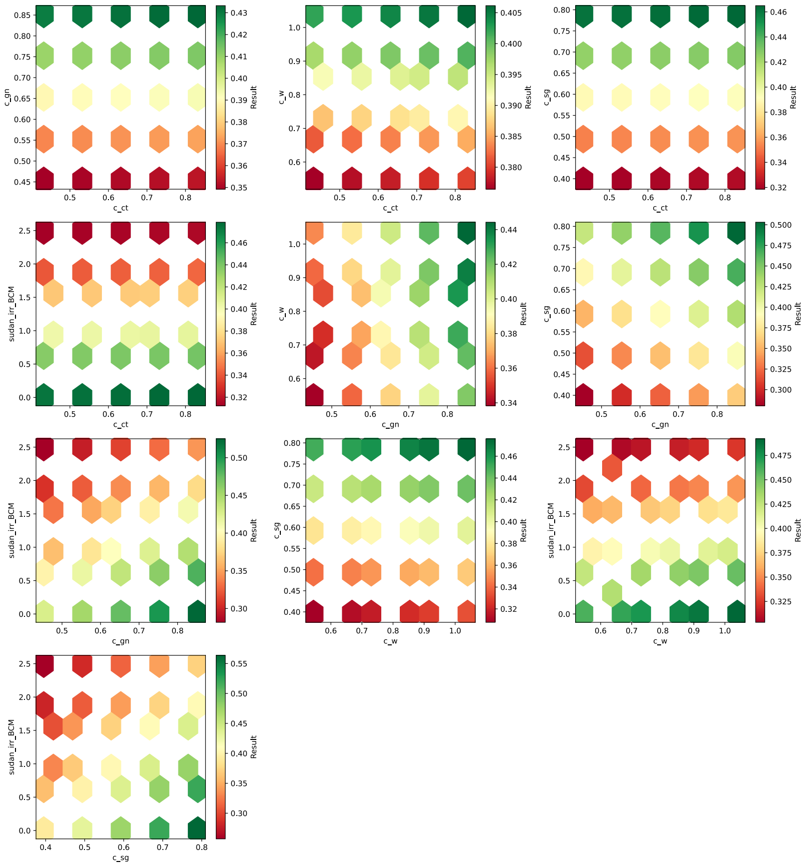
8. WATER USAGE VARIATION: UTILITY FROM SUDAN IRRIGATION DEMAND DEFICIT



9. YIELD VARIATION: UTILITY FROM SUDAN IRRIGATION DEMAND DEFICIT



10. COST VARIATION: UTILITY FROM SUDAN IRRIGATION DEMAND DEFICIT



11. SENSITIVITY ANALYSIS PARAMETER VALUES

HAD Utility (Egypt)

Parameter	**Units**	**Low Value**	**Value Step**	**High Value**
Frequency of HAD low-water levels	decimal percent	0.00	0.10	1.00
Cost of hydropower	USD/kWh	0.05	0.03	0.20
Base annual hydropower production for the HAD	GWh	8000.00	1000.00	14000.00

Irrigation Utility (Egypt)

Costs of sale				
Cost, barley	USD/kg	0.19	0.03	0.34
Cost, corn	USD/kg	0.27	0.10	0.57
Cost, cotton	USD/kg	0.19	0.05	0.35
Cost, groundnuts	USD/kg	3.16	0.50	5.66
Cost, soybeans	USD/kg	0.24	0.10	0.54
Cost, sorghum	USD/kg	0.13	0.05	0.24
Cost, wheat	USD/kg	0.29	0.10	0.59
Cost, rice	USD/kg	0.15	0.06	0.33
Yield of crop				
Yield, barley	kg/sq m	0.09	0.02	0.15
Yield, corn	kg/sq m	0.60	0.10	0.90
Yield, cotton	kg/sq m	0.05	0.02	0.09
Yield, groundnuts	kg/sq m	0.23	0.03	0.35
Yield, soybeans	kg/sq m	0.20	0.04	0.32
Yield, sorghum	kg/sq m	0.40	0.03	0.52
Yield, wheat	kg/sq m	0.48	0.06	0.72
Yield, rice	kg/sq m	0.60	0.10	0.90
Water usage of crop				
Water usage, barley	cb m/ sq m	0.34	0.10	0.64
Water usage, corn	cb m/ sq m	0.63	0.20	1.23
Water usage, cotton	cb m/ sq m	0.93	0.20	1.73
Water usage, groundnuts	cb m/ sq m	0.68	0.20	1.28
Water usage, soybeans	cb m/ sq m	0.70	0.20	1.30
Water usage, sorghum	cb m/ sq m	0.65	0.20	1.25
Water usage, wheat	cb m/ sq m	0.45	0.10	0.85
Water usage, rice	cb m/ sq m	0.86	0.20	1.66
Area of crop				
Area, barley	1000 ha	48.00	20.00	108.00
Area, corn	1000 ha	585.00	200.00	1185.00
Area, cotton	1000 ha	67.00	20.00	127.00
Area, groundnuts	1000 ha	45.00	20.00	85.00
Area, soybeans	1000 ha	6.00	2.00	12.00
Area, sorghum	1000 ha	106.00	20.00	206.00
Area, wheat	1000 ha	952.00	200.00	1752.00
Area, rice	1000 ha	446.00	100.00	846.00
Egypt Irrigation Deficit	BCM/year	3.00	4.00	18.00

Ethiopian GERD Hydropower Production Utility

Parameter	**Units**	**Low Value**	**Value Step**	**High Value**
Cost of hydropower, exports	USD/kWh	0.00	0.04	16.00
Percentage of hydropower exported	decimal percent	0.05	0.03	0.14
Cost of hydropower, domestic	USD/kWh	0.01	0.03	0.10
Percentage of hydropower, domestic	decimal percent	0.05	0.03	0.17
GERD Production Value	TWh/year	12.00	1.00	16.00

Irrigation Utility (Sudan)

Parameter	**Units**	**Low Value**	**Value Step**	**High Value**
Costs of sale				
Cost, cotton	USD/kg	0.43	0.10	0.83
Cost, groundnuts	USD/kg	0.45	0.10	0.85
Cost, wheat	USD/kg	0.54	0.10	1.04
Cost, sorghum	USD/kg	0.40	0.10	0.80

Yield of crop				
Yield, cotton	kg/sq m	0.03	0.01	0.07
Yield, groundnuts	kg/sq m	0.05	0.01	0.09
Yield, wheat	kg/sq m	0.15	0.05	0.30
Yield, sorghum	kg/sq m	0.04	0.01	0.07
Water usage of crop				
Water usage, cotton	cb m/ sq m	0.40	0.10	0.80
Water usage, groundnuts	cb m/ sq m	0.70	0.10	1.20
Water usage, wheat	cb m/ sq m	0.25	0.05	0.45
Water usage, sorghum	cb m/ sq m	0.57	0.10	1.07
Area of crop				
Area, cotton	1000 ha	135.00	50.00	285.00
Area, groundnuts	1000 ha	2176.00	300.00	4276.00
Area, wheat	1000 ha	190.00	30.00	340.00
Area, sorghum	1000 ha	5220.00	500.00	9720.00
Sudan Irrigation Deficit	BCM/year	0.00	0.50	2.50

D. SUPPLEMENTAL: BASELINE ANALYSIS

1. INDIVIDUAL EUCLIDEAN DISTANCE VALUES

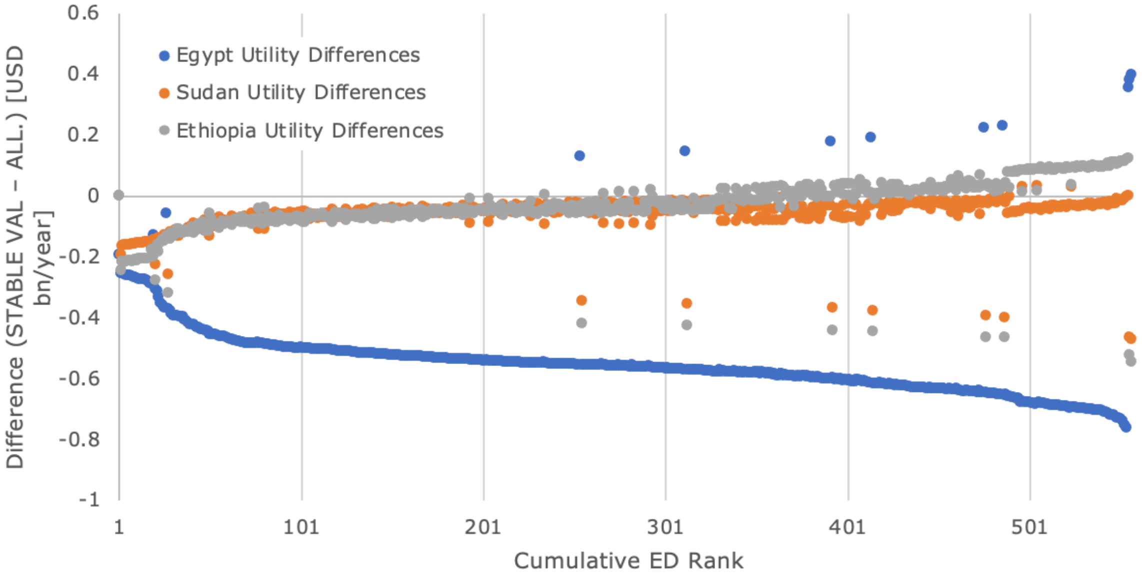


Figure D.1: Individual distance values for each nation, shown to be changing from most stable to least stable policy for the baseline analysis. Note that Egypt's "runaway" utility phenomenon is portrayed here, how there is a continuous increase of Egypt's utility as policies become more unstable.

2. RANKING DISTRIBUTIONS

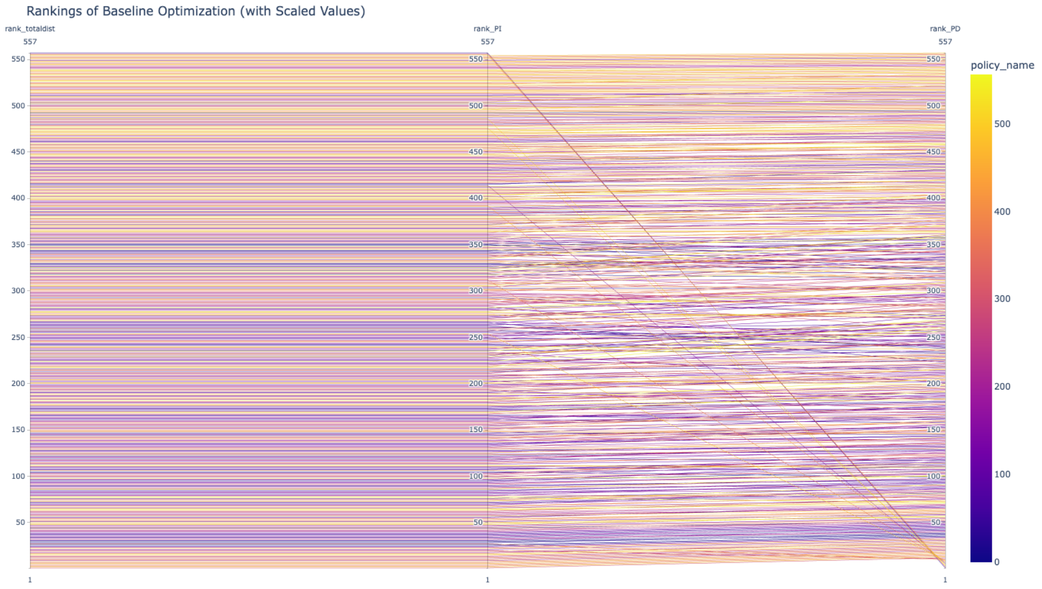


Figure D.2: Parallel Coordinate Plot for Baseline Analysis showing changes in Ranking due to Stability Metric differences. **Terminology:** "rank_totaldist" = rankings based on Euclidean Distance; "rank_PI" = rankings based on power index; "rank_PD" = rankings based on the propensity to disrupt.

E. SUPPLEMENTAL: CORE

1. CORE CALCULATION PROOF

The Core of a game is the set of all stable outcomes that all players can have in a game *G*. The series of inequalities developed for the calculation of the Core (using equations 3.3.1) must satisfy the *individual rationality, group rationality,* and *efficiency* paradigms.

$$\begin{gathered}\omega_E \geq 5.12574\\ \omega_S \geq 0.460925\\ \omega_{Et} \geq 0.463206\\ \omega_E + \omega_S \geq 6.344068\\ \omega_E + \omega_{Et} \geq 6.223809\\ \omega_S + \omega_{Et} \geq 0.925906\\ \omega_E + \omega_S + \omega_{Et} = 6.68192\end{gathered}$$

Inequality Determination for $\boldsymbol{\omega_E}$

$\omega_S + \omega_{Et} = 6.68192 - \omega_E$
$6.68192 - \omega_E \geq 0.925906$
$\therefore \mathbf{5.75608} \geq \boldsymbol{\omega_E}$

Since the individual rationality condition for ω_E must hold, the bounds for a potentially stable allocation of ω_E must be

$$\mathbf{5.75608} \geq \boldsymbol{\omega_E} \geq \mathbf{5.12574}$$

Inequality Determination for $\boldsymbol{\omega_S}$

$\omega_E + \omega_{Et} = 6.68192 - \omega_S$
$6.68192 - \omega_S \geq 6.223809$

$$\therefore \mathbf{0.45383} \geq \boldsymbol{\omega_S}$$

However, since the individual rationality condition for ω_S must hold, there is a mathematical contradiction, and thus the bounds for a potentially stable allocation of ω_S are not possible. Therefore, the **Core is empty.**

2. Epsilon-Core Calculation

The *Epsilon*-Core calculations must occur due the Core being empty. For the *Epsilon-Core,* the series of inequalities developed for the calculation of the Core must satisfy the *individual rationality, group rationality,* and *efficiency* paradigms. However, the only difference is that a deduction ε is made in the inequality to loosen the Core's confines in order to find approximately stable allocation positions. The *Epsilon*-Core's equation is given by Equation 3.3.4. Each symbol corresponds to the definition given in the calculation of the Core in Appendix E.1.

$$\omega_E \geq 5.12574 - \varepsilon$$
$$\omega_S \geq 0.460925 - \varepsilon$$
$$\omega_{Et} \geq 0.463206 - \varepsilon$$
$$\omega_E + \omega_S \geq 6.344068 - \varepsilon$$
$$\omega_E + \omega_{Et} \geq 6.223809 - \varepsilon$$
$$\omega_S + \omega_{Et} \geq 0.925906 - \varepsilon$$

Note that, for the *Efficiency* paradigm to still be valid, including the deduction ε would be redundant, so we keep the original equality as from the Core, which will mathematically encompass the deduction.

$$\omega_E + \omega_S + \omega_{Et} = 6.68192$$

Inequality Determination for ω_E

$$\omega_S + \omega_{Et} = 6.68192 - \omega_E$$
$$6.68192 - \omega_E \geq 0.925906 - \varepsilon$$
$$\therefore \mathbf{5.75608} \geq \boldsymbol{\omega_E} - \boldsymbol{\varepsilon}$$

Inequality Determination for ω_S

$$\omega_E + \omega_{Et} = 6.68192 - \omega_S$$
$$6.68192 - \omega_S \geq 6.223809 - \varepsilon$$
$$\therefore \mathbf{0.4581} \geq \boldsymbol{\omega_S} - \boldsymbol{\varepsilon}$$

Inequality Determination for ω_{Et}

$$\omega_E + \omega_S = 6.68192 - \omega_{Et}$$
$$6.68192 - \omega_{Et} \geq 6.344068 - \varepsilon$$
$$\therefore \mathbf{0.3378} \geq \boldsymbol{\omega_{Et}} - \boldsymbol{\varepsilon}$$

Solving the three inequalities with with the *efficiency* paradigm, we get the following solution:

$$\varepsilon \geq 0.062$$
$$\omega_E = 5.886 - 2\varepsilon$$
$$\omega_S = 0.4581 + \varepsilon$$
$$\omega_{Et} = 0.3378 + \varepsilon$$

3. Epsilon-Core Bounds

Table E.2: Ranges for near-efficient solutions for different nations when applied various ε value intervals. A higher ε represents a higher deduction from coalition values to form an acceptable solution for all nations.

Epsilon	**Egypt, Low Bound**	**Egypt, High Bound**	**Sudan, Low Bound**	**Sudan, High Bound**	**Ethiopia, Low Bound**	**Ethiopia, High Bound**
0.067	5.059	5.823	0.394	0.525	0.396	0.405
0.16	4.966	5.916	0.301	0.618	0.303	0.498
0.19	4.936	5.946	0.271	0.648	0.273	0.528
0.29	4.836	6.046	0.171	0.748	0.173	0.628
0.39	4.736	6.146	0.071	0.848	0.073	0.728

F. SUPPLEMENTAL: SHAPLEY VALUE

1. *RANKING DISTRIBUTIONS, SYMMETRIC SHAPLEY VALUE*

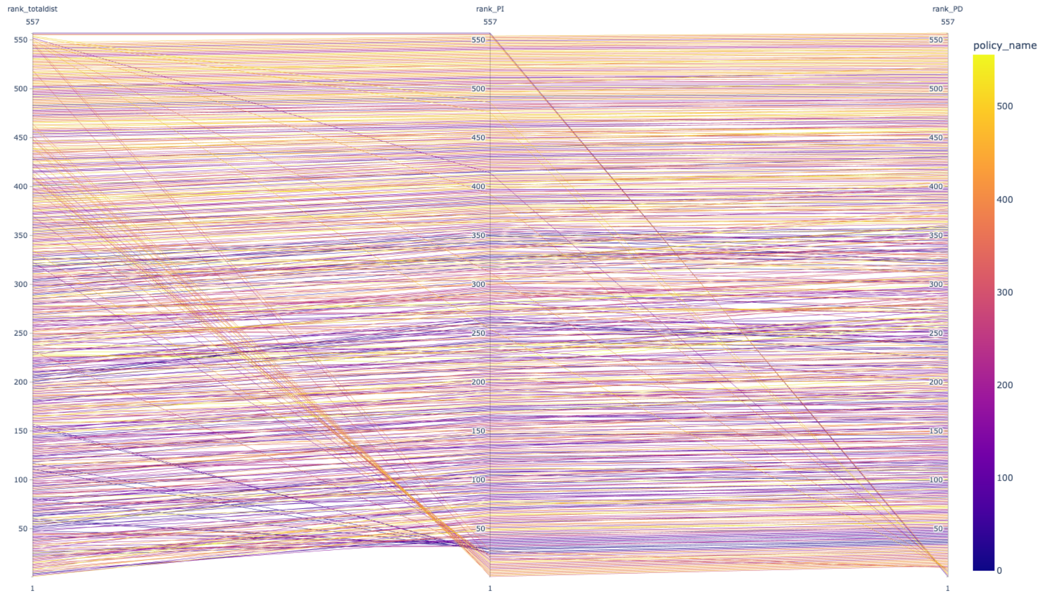


Figure F.1: A parallel coordinate plot for the symmetric Shapley Value showing changes in rank order across different metrics. **Terminology:** "rank_totaldist" = rankings based on Euclidean Distance; "rank_PI" = rankings based on power index; "rank_PD" = rankings based on the propensity to disrupt. As seen, there are minimal changes between most ranks. Policies with large transitions in ranks are mainly a result of boundary errors.

2. *UTILITY DISTRIBUTIONS – ED RANKING*

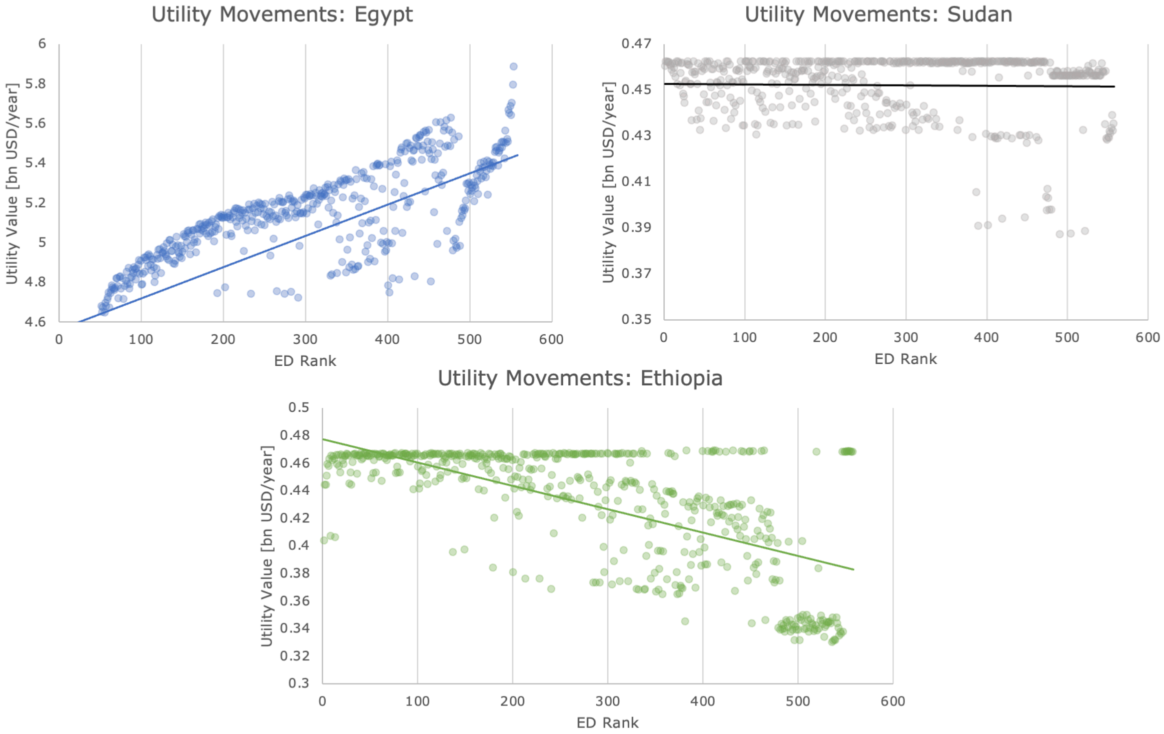


Figure F.2: Utility Movements to each Nation from most stable to least stable policy (based on Euclidean Distance).

3. Weighted Shapley Values – Metric Distributions per ED rank

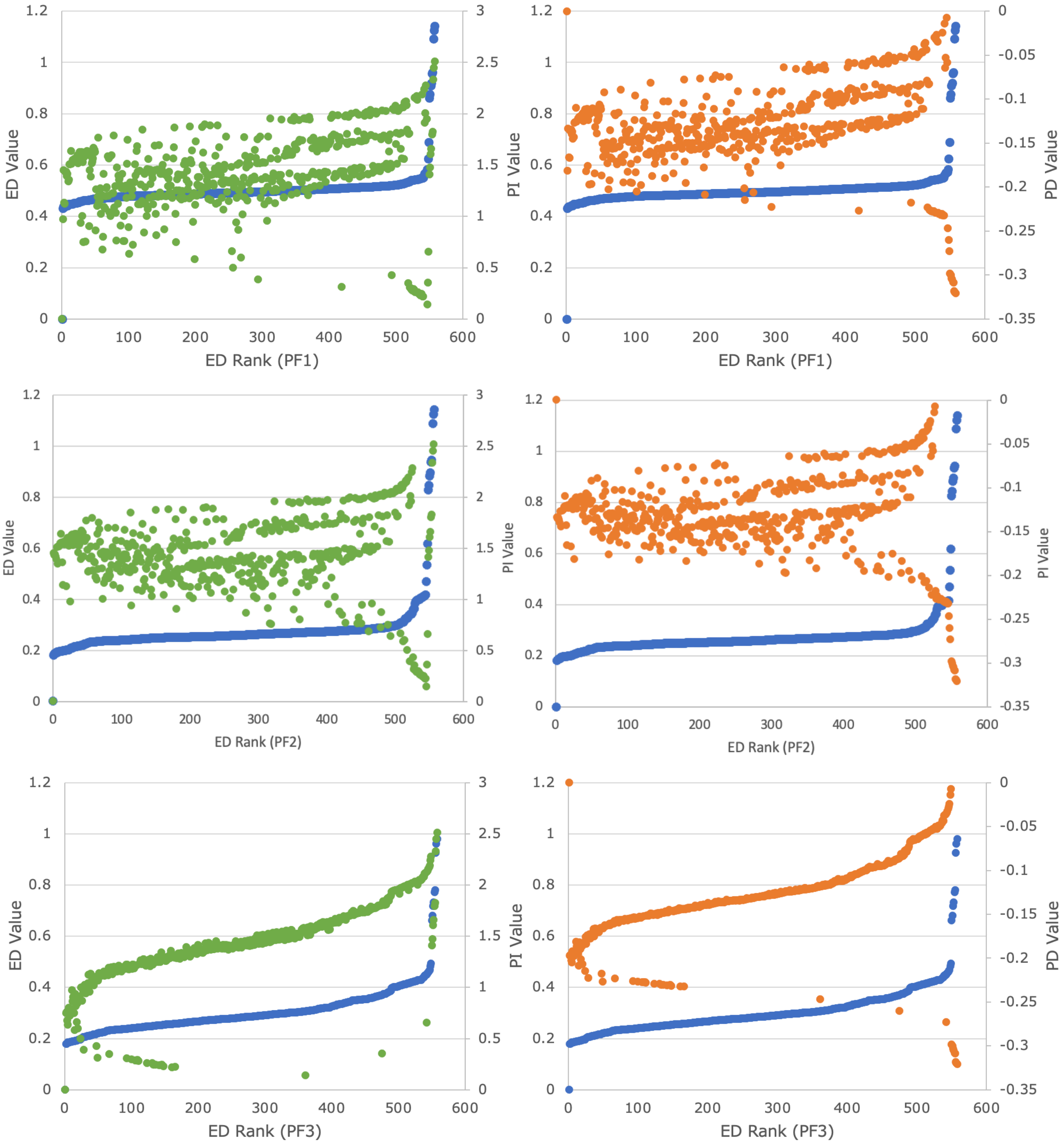


Figure F.3: For each problem formulation, a distribution of each metric's value plotted against the Euclidean Distance rank. Notice that with each problem formulation (each one closer to the cluster of policy candidates), the PI and PD values significantly reduced variance and grew proportionally with the ED value.

4. Utility Progression of Weighted Shapley Values

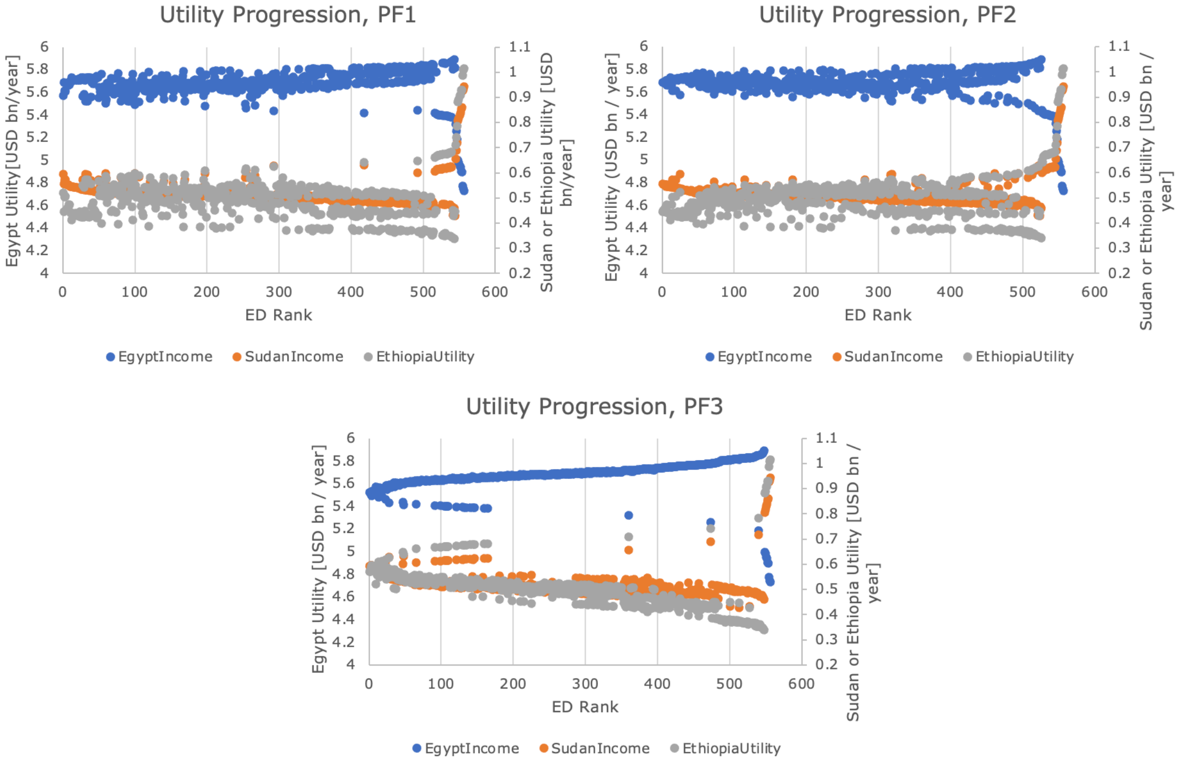


Figure F.4: Utility progressions across different weighted Shapley Values.

G. SUPPLEMENTAL: NASH-HARSANYI ALLOCATION

1. *RANKING DISTRIBUTIONS, SYMMETRIC NASH-HARSANYI SOLUTION*

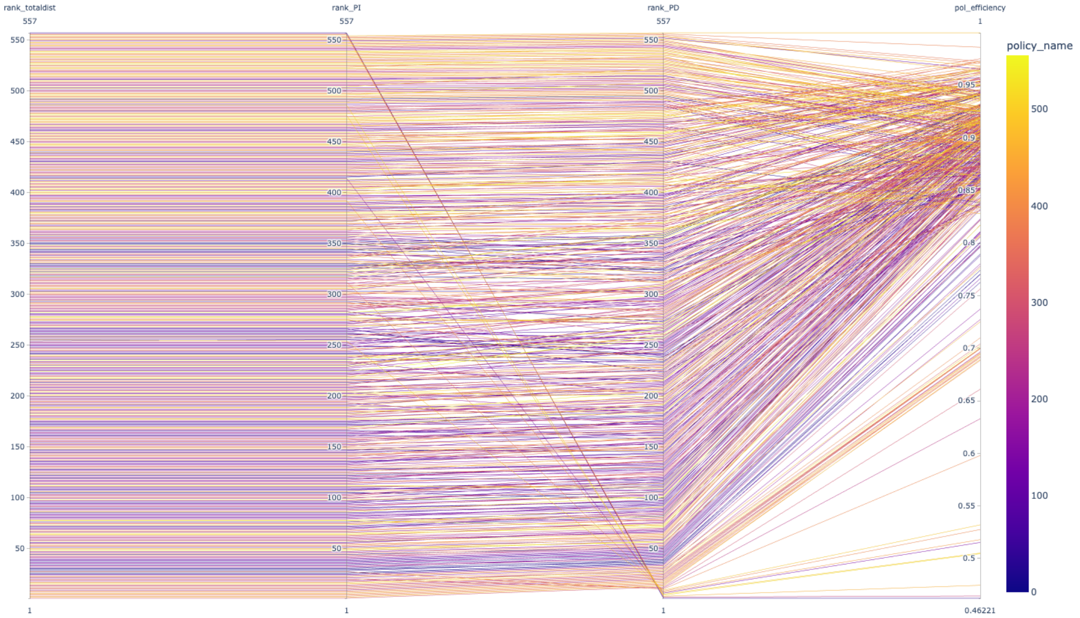


Figure G.1: A Parallel Coordinate Plot for the symmetric Nash-Harsanyi Solution. Policy Efficiency is also shown to explore trade-offs. **Terminology:** “rank_totaldist” = rankings based on Euclidean Distance; “rank_PI” = rankings based on power index; “rank_PD” = rankings based on the propensity to disrupt.

2. *STABILITY RANK PROGRESSIONS, SCENARIO 1*

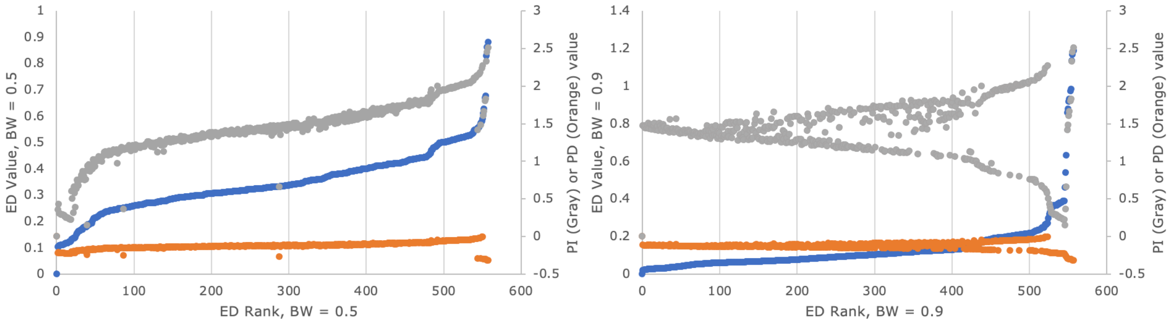


Figure G.2: Movement of PI and PD Indices based on ED Metrics ranking at different bargaining weights for asymmetric Nash-Harsanyi Solution for dominant player as Egypt.

3. UTILITIES AND OBJECTIVES TRADEOFFS, SCENARIO 1

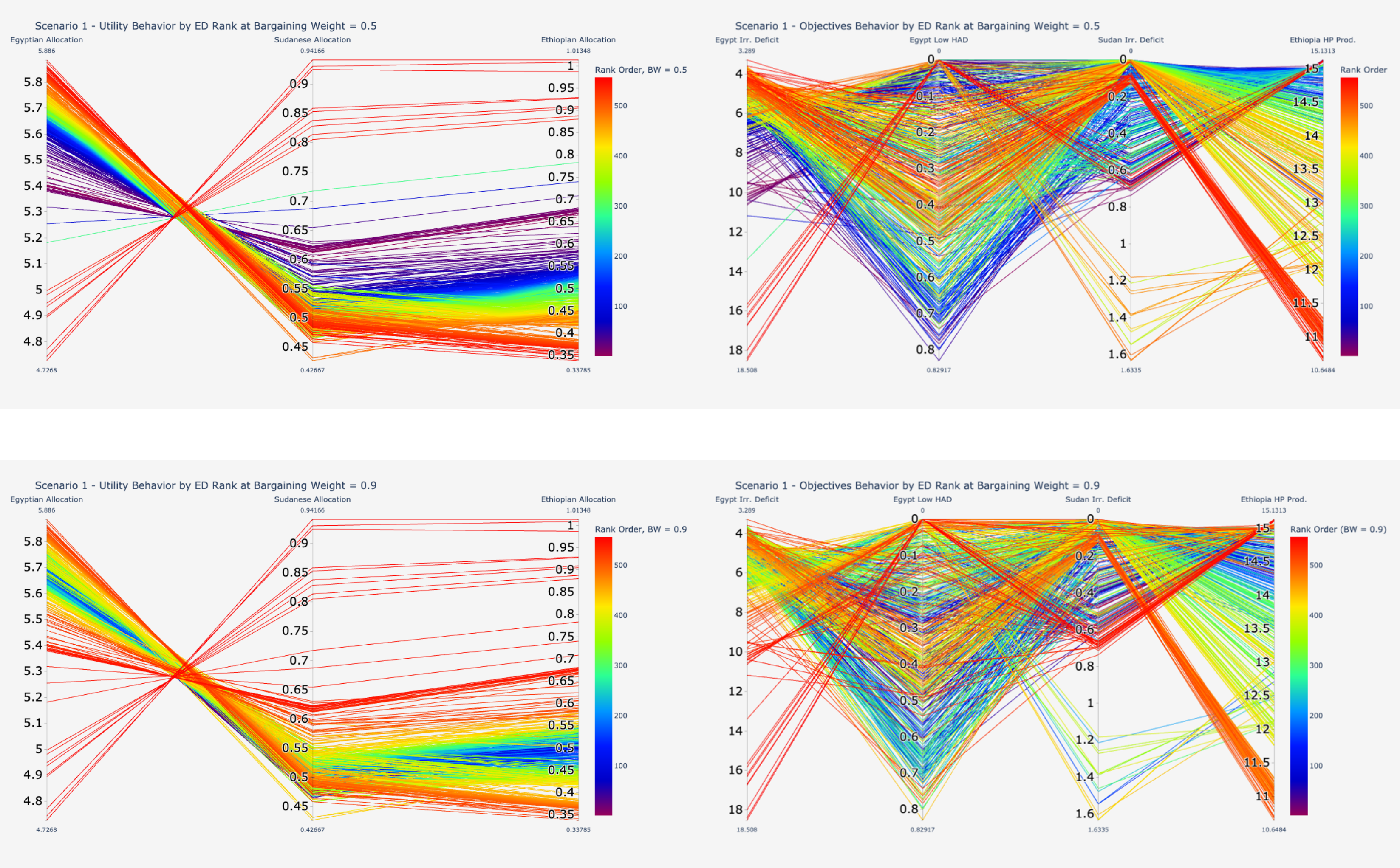


Figure G.3: Parallel coordinate plots showing the movement of stable policies for asymmetric Nash-Harsanyi solutions for Scenario 1. (1, *top left*) Utility with BW (Egypt) = 0.5; (2, *top right*) Objectives with BW (Egypt) = 0.5; (3, *bottom left*) Utility with BW(Egypt) = 0.9; (4, *bottom right*) Objectives with BW(Egypt) = 0.9.

4. METRIC DISTRIBUTIONS – SCENARIO 2

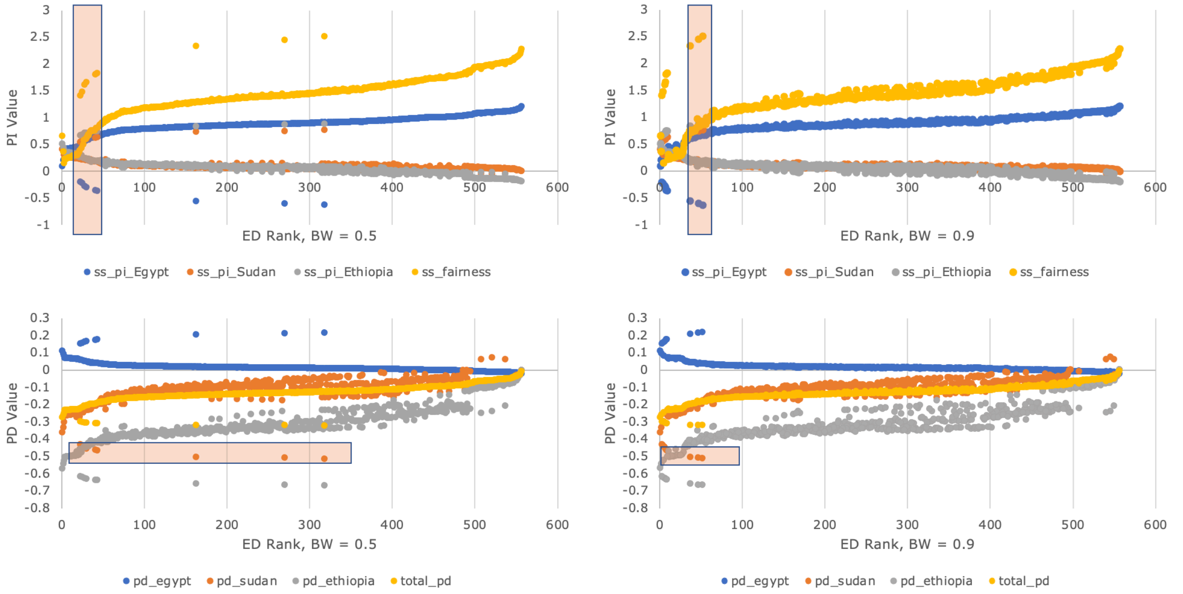


Figure G.4: Distribution of cumulative metrics and individual metric values (PI and PD) for Sudan’s bargaining weights of 0.5 and 0.9. Boxes are areas of interest. **Terminology:** “ss_pi_egypt” = power index, Egypt; “ss_pi_sudan” = power index, Sudan; “ss_pi_Ethiopia” = power index, Ethiopia; “ss_fairness” = fairness index value; “pd_egypt” = Propensity to disrupt, Egypt; “pd_sudan” = Propensity to disrupt, Sudan; “pd_ethiopia” = Propensity to disrupt, Ethiopia; “total_pd” = Average propensity to disrupt.

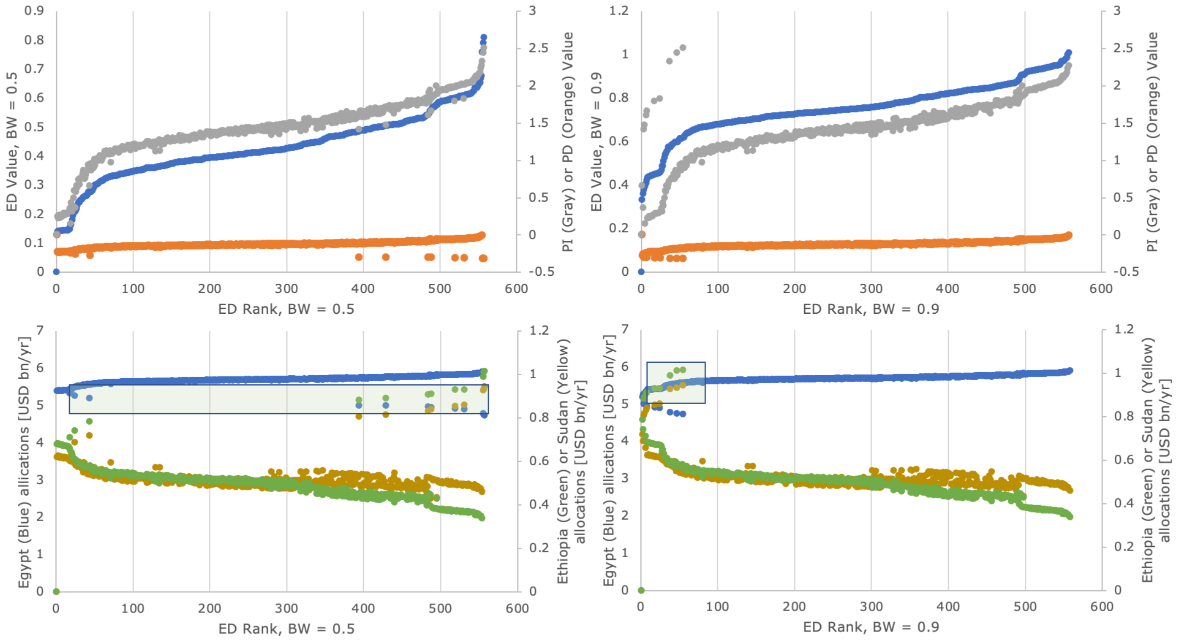


Figure G.5: Distributions of cumulative stability metrics and individual nation's allocations. Boxes show that as the bargaining weight of the dominant country increases, we see a reorder to bring high-allocation policies as more stable policies.

5. METRIC DISTRIBUTIONS – SCENARIO 3

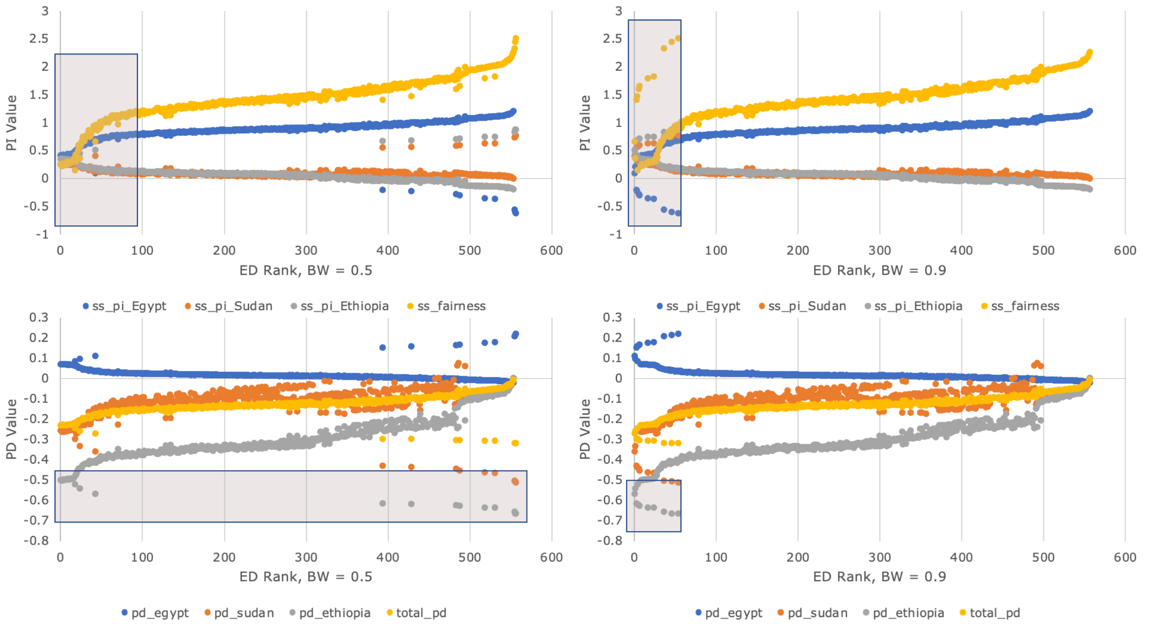


Figure G.6: Distribution of cumulative metrics and individual metric values (PI and PD) for Ethiopian bargaining weights of 0.5 and 0.9. Similar to Figure G.4, the high-allocation policies become among the most stable policies as the bargaining weight of the dominant country increases. **Terminology:** "ss_pi_egypt" = power index, Egypt; "ss_pi_sudan" = power index, Sudan; "ss_pi_Ethiopia" = power index, Ethiopia; "ss_fairness" = fairness index value; "pd_egypt" = Propensity to disrupt, Egypt; "pd_sudan" = Propensity to disrupt, Sudan; "pd_ethiopia" = Propensity to disrupt, Ethiopia; "total_pd" = Average propensity to disrupt.

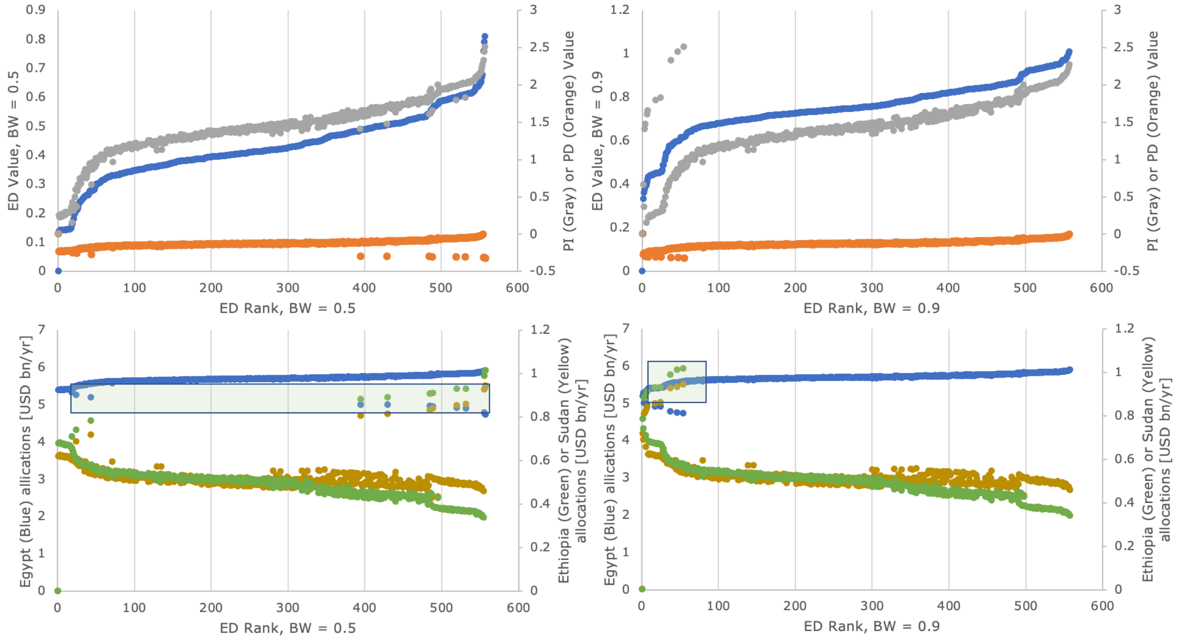


Figure G.7: Distributions of cumulative stability metrics and individual nations' allocations when Ethiopia is the dominant player.

H. Supplemental: Nucleolus

1. PD Progressions (based on Euclidean Distance rank)

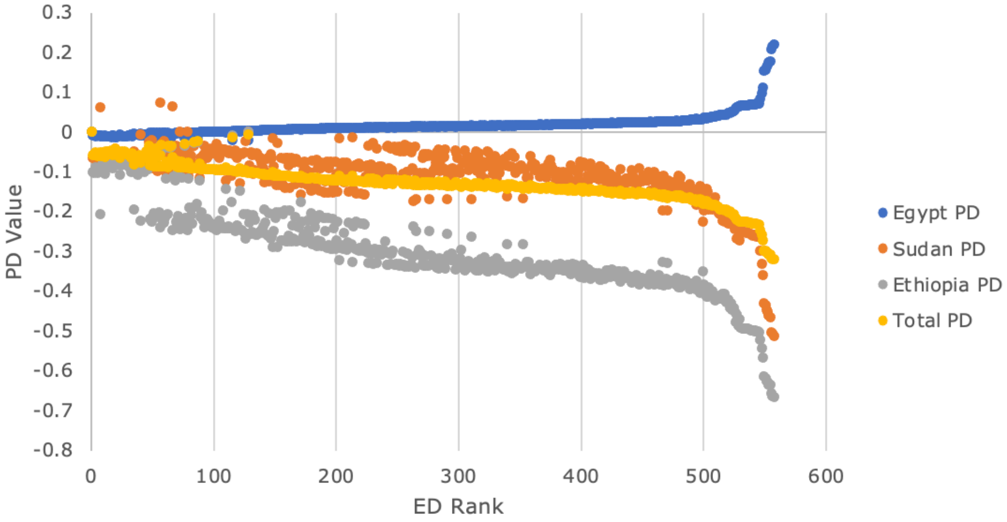


Figure H.1: Distributions of propensity to disrupt (PD) values, ordered by Euclidean Distance rank determined with use of the nucleolus. Notice that this is an inverted behavior as to what was seen in other solution concepts, where PD values converged due to Egypt's high allocation and Ethiopia and Sudan's decreasing loss value as compared to the grand coalition. In the nucleolus, we see a diverging value.

2. Rankings Distribution: Nucleolus

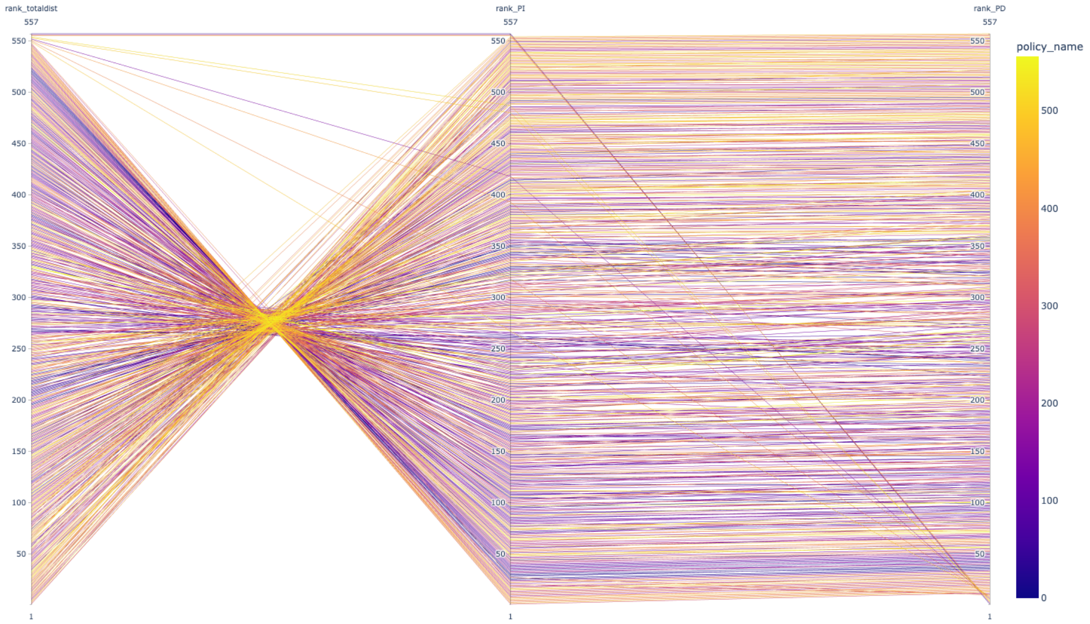


Figure H.2: Parallel Coordinate Plots showing the rank changes based on Stability Metric for the nucleolus. "rank_totaldist" refers to ranks based on Euclidean Distance; "rank_PI" refers to ranks based on power index; "rank_PD" refers to ranks based on the propensity to disrupt.

Table H.3: A table of the subset of policy candidates identified in Section 5.3. While PI (power index) and PD ranks remain the same, differences in rank based on the major solution concepts (barring the asymmetric versions) are provided. Note that the ranking direction of preference still applies as seen above; a rank value of 1 is most preferred and is considered the most stable allocation, while a rank of 557 represents the least stable allocation. Highlighted rows indicate the compromise policies that are discussed in Section 7.2.

									BA	*Sym. Shapley Value*	*Sym. Nash-Harsanyi Solution*	*Nucleolus*		
Policy	**Policy Number**	**Total Policy Eff.**	**Egypt Utility [bn USD/yr]**	**Egypt Policy Eff.**	**Sudan Utility [bn USD/yr]**	**Sudan Policy Eff.**	**Ethiopia Utility [bn USD/yr]**	**Ethiopia Policy Eff.**	**ED Rank**				**PI Rank**	**PD Rank**
Best Egypt Irr. Policy	483	1.00	5.89	1.00	0.46	0.99	0.34	0.72	554	547	554	128	554	557
Best Egypt Low HAD Level Policy	96	0.82	5.58	0.78	0.56	1.00	0.54	0.95	51	3	51	494	51	59
Best Egypt Low HAD Level Policy	102	0.87	5.67	0.84	0.53	1.00	0.48	0.90	226	180	226	302	226	214
Best Egypt Low HAD Level Policy	149	0.92	5.56	0.90	0.57	1.00	0.55	0.81	46	2	46	500	46	55
Best Egypt Low HAD Level Policy	157	0.74	5.43	0.68	0.63	1.00	0.62	0.98	21	323	21	527	33	41
Best Egypt Low HAD Level Policy	253	0.87	5.64	0.83	0.53	1.00	0.51	0.94	142	95	142	401	142	138
Best Ethiopia HP Policy	475	0.70	5.40	0.64	0.61	0.93	0.67	1.00	15	411	15	533	15	26
Absolute Threshold Policy	329	0.93	5.71	0.90	0.50	1.00	0.47	0.94	356	333	356	188	356	366
Percentile Threshold Policy	106	0.91	5.68	0.87	0.51	1.00	0.49	0.96	249	210	249	284	249	247

I. Supplemental: Discussion

5. *Policy Ranking Distribution: All CGT Solution Concepts*

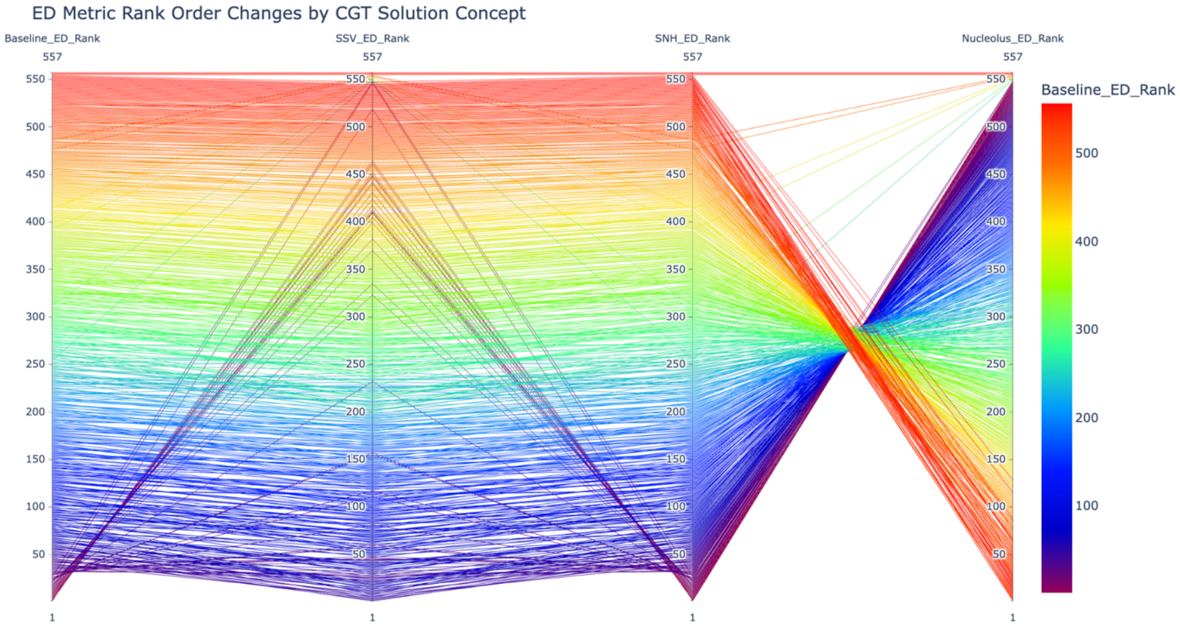


Figure I.1: A parallel coordinate plot showing the overall differences in ranks seen between policies from the baseline analysis to the nucleolus. Overall, we see a fairly consistent movement between the policy's rank and their behaviors (except when considering the nucleolus). **Terminology:** "ED" = Euclidean distance; SSV = "symmetric Shapley Value"; SNH = "symmetric Nash-Harsanyi solution"

6. *Distances between Solution Concepts*

Table I.2: Distances between each solution concept, showing one possibility as to the similar behaviors across different solution concepts. Values can be interpreted in [USD billion per year].

	BA	**SSV**	**PF1**	**PF2**	**PF3**	**SNH**
BA	0.000					
SSV	0.464	0.000				
PF1	0.796	0.439	0.000			
PF2	0.597	0.216	0.280	0.000		
PF3	0.295	0.188	0.549	0.314	0.000	
SNH	0.365	0.287	0.546	0.431	0.280	0.000
Nuc	0.696	0.307	0.540	0.310	0.418	0.592