From inference to influence: applying causal game theory to complex security environments

Vonk, M.C.

Chapter 1

Introduction

Strategic studies has long grappled with the challenge of understanding complex interactions between actors operating in uncertain and contested environments. Scholars and practitioners examining military conflicts, diplomatic negotiations, or security decisions seek analytical frameworks to support policy interventions. The field now employs formal methodologies from economics, mathematics, and social sciences to analyze strategic behavior, recognizing that intuition alone cannot resolve strategic problems.

Game-theoretical approaches are well established within strategic studies, offering robust tools for analyzing strategic interaction and decision-making under adversarial conditions [144, 101, 18]. In contrast, applications of causal inference remain notably limited. This absence is striking, given that effective policy intervention relies on identifying the causal effects of actions and distinguishing them from spurious correlations. Without a clear understanding of underlying causal mechanisms, policy decisions risk being based on misleading evidence, potentially resulting in unintended or ineffective outcomes. Causal inference, therefore, provides an essential foundation for formulating interventions that are both evidence-based and contextually appropriate.

To understand why causal inference has been underutilized in strategic studies, it is essential to examine the methodological challenges that have historically made causal claims difficult to establish. The study of causality has evolved significantly over time, rooted in philosophical and empirical traditions. David Hume, in the 18th century, argued that causation could not be directly observed but only inferred through regular associations and temporal ordering. This foundational problem, the impossibility of simultaneously observing both what happens when an intervention occurs and what

would have happened without it, was later formalized as the *fundamental problem of causal inference*. Researchers have thus traditionally exercised caution in making causal claims. One major response to this problem was the development of *randomized controlled trials* (RCTs), which offer a systematic approach to identifying causal effects by randomly assigning units to treatment and control groups, thereby eliminating bias from confounding variables. However, RCTs are often impractical or unethical in many settings, limiting their applicability.

This limitation gave rise to a rich body of work focused on causal inference using observational data. Donald Rubin advanced the potential outcomes framework. This framework offers a formal structure for thinking about *counterfactuals*, hypothetical outcomes that would have occurred under different treatment conditions [202]. Judea Pearl developed causal graphical models and the do-calculus, which provided a systematic approach that employed visual representations and mathematical operations to identify causal relationships from observational data [178]. Pearl also made a crucial distinction between causal discovery and causal inference. While *causal discovery* is concerned with identifying the underlying causal structure between variables by examining their statistical relationships, *causal inference* is concerned with probabilistically estimating an outcome variable under possible alterations. Pearl further refined causal inference by classifying it into three levels of increasing complexity, as outlined in his *causal hierarchy* [27]. Addressing queries at the more advanced levels often requires specialized causal calculi, which transform complex queries into solvable components, a process known as *causal identification*. Causal identification enables the implementation of *causal interventions*, manipulations of one variable that induce changes in others. In parallel, Joshua Angrist and Guido Imbens developed techniques for leveraging natural experiments, particularly instrumental variables [117]. Instrumental variables are factors that affect treatment assignment but have no direct effect on the outcome, allowing researchers to infer causality. Their contributions were recognized with the 2021 Nobel Prize in Economics, underscoring the maturation of causal inference as a rigorous scientific field.

These theoretical advancements have found extensive application in medical research and epidemiology, where establishing causal relationships is fundamental to understanding disease mechanisms and evaluating treatment effectiveness. However, the social sciences have adopted these methodological innovations more slowly, despite their clear relevance for the analysis of complex social and political processes. In the social sciences, approaches to causality have been fundamentally shaped by interpretive traditions, most notably Max Weber's methodological framework. Weber distin-

guished between *verstehen* (interpretive understanding) and *erklären* (causal explanation), arguing that effective social scientific analysis required both approaches working in tandem rather than viewing them as opposing methodologies. He sought to develop causal explanations that incorporated actors' subjective orientations within their specific historical and cultural contexts. Weber's insights remain particularly relevant because they anticipate a fundamental problem that becomes especially pronounced in strategic studies: the need to account for how actors' subjective interpretations of causal relationships shape their strategic responses, which in turn alter the very causal dynamics being analyzed.

Building on these general difficulties in social science methodology, security studies, as an application of strategic studies, faces a core analytical challenge that makes causal models particularly problematic. Complex security environments feature the convergence of interrelated threats, including armed violence, political fragility, socioeconomic instability, environmental stress, and multi-domain conflict dynamics, all shaped by interactions among multiple state and non-state actors. These characteristics systematically violate the fundamental assumptions underlying standard causal inference methods. Most critically, such environments exhibit widespread interference effects, where policy interventions could spread beyond their intended targets, affecting neighboring actors and outcomes. This makes it impossible to isolate causal effects cleanly. Simultaneously, strategic interdependence means that actors continuously monitor and adapt their behaviors in response to observed interventions by others. When security policies are implemented, adversaries do not passively accept their effects but actively counter-adapt, developing new tactics, shifting resources, or altering their strategic calculations in ways that change the very causal relationships that analysts seek to understand. In essence, interference and strategic considerations, among other characteristics, cause standard causal models to fail in complex security environments.

This analytical challenge, combined with difficulties in both comprehension and implementation of sophisticated methods [41, 165, 99], has led to a persistent lack of causal inference applications in complex security environments. The mathematical complexity of existing approaches often renders them inaccessible to security scholars and practitioners, while their computational requirements can present additional barriers for policy-makers operating under time pressure and resource limitations. This implementation gap has prompted increasing calls to bridge the divide between theory and practice through structured dialogues and closer collaborations between practitioners and methodologists [223, 165].

Addressing this challenge is crucial for several reasons. First, the characteristics of complex security environments demand analytical approaches that can match this complexity with methodological sophistication. Without them, analysts risk providing misleading or incomplete policy advice that undermines effective intervention. Second, causal inference methods must demonstrate their adaptability beyond computer science domains to establish broader disciplinary relevance and prevent methodological isolation. Third, real-world applications in complex security contexts reveal methodological limitations and drive the development of more sophisticated causal models, advancing the field through exposure to practical demands.

To address this issue, this dissertation develops an integrated framework that enables the application of causal inference in complex security environments. It adapts core causal concepts to reflect the specific features of such contexts, introduces computationally efficient methods for estimating intervention effects, and derives insights from real-world empirical applications.

1.1 Research Questions

This investigation is structured around three main research questions, which are further broken down into the following sub-research questions.

RQ1: **What conceptual frameworks and assumptions are necessary to enable the modeling of causal game theory in complex security environments?**

- RQ1.1: What fundamental causal concepts are necessary for structuring and differentiating causal relationships, particularly in the context of Pearl's causal hierarchy?
- RQ1.2: What key assumptions underpin causal inference applications across Pearl's causal hierarchy?
- RQ1.3: What methods exist for integrating causal reasoning with strategic decision-making in complex security environments, and how can they be applied?

RQ2: **How can optimal causal interventions be computed with high accuracy while ensuring computational efficiency?**

- RQ2.1: How can inference be performed efficiently to accurately estimate the effects of causal interventions while maintaining computational feasibility?

RQ2.2: How can optimization techniques be integrated with causal inference to optimize over causal interventions efficiently under budget constraints?

RQ3: **How can the proposed (strategic) causal concepts be applied to complex security environments?**

1.2 Contributions

In addressing these research questions, the dissertation makes theoretical, methodological, empirical, and societal contributions. Theoretical and methodological contributions establish a framework for causal reasoning in strategic contexts, while empirical applications to hybrid threats and climate conflict constitute the societal contributions by providing actionable insights for policymakers and security practitioners.

This thesis makes two primary *theoretical* contributions. First, it systematically organizes fragmented causal inference methods within Pearl's causal hierarchy, which structures causal reasoning across three levels: association, intervention, and counterfactual. This mapping clarifies the assumptions required at each level and enables practitioners to align specific policy questions with appropriate causal tools. Second, the thesis integrates strategic interaction within causal concepts using probabilistic graphical models, synthesizing the connections between diverse game forms such as normal form games, extensive form games, and Bayesian games and their causal representations. This theoretical unification articulates the mathematical distinctions between these models, clarifying which causal and strategic structures are required for different analytical contexts.

Regarding the *methodological* contribution, the thesis develops novel computational methods that address implementation barriers preventing causal inference application in complex security contexts. This contribution consists of an efficient approach for approximating the effect of causal interventions in hybrid Bayesian networks, combining discretization with knowledge compilation techniques. The approximation method is embedded within an optimization framework that identifies the most effective interventions under resource constraints. These methodological innovations transform computationally intractable problems into practical policy analysis tools.

The thesis makes an *empirical* contribution through two applications in complex security environments. The Iraq environmental conflict analysis uses causal discovery methods to uncover causal mechanisms linking environmental variables to conflict. The analysis computes causal estimates while accounting for spatial interference be-

tween municipalities. The hybrid threat deterrence application shows how strategic causal models establish equilibria between deterring and attacking agents. Sensitivity analysis reveals which factors most influence equilibrium outcomes. These studies provide new empirical insights into the role of causal mechanisms, interference, and strategic interaction in complex security settings.

The thesis makes a *societal* contribution by providing policymakers with practical tools and evidence-based findings for complex security environments. The empirical applications offer findings for formulating interventions in environmental conflict situations, while accounting for causal mechanisms and regional spillover. In hybrid threat scenarios, the application show how policymakers can assess the likely effects of measures in the presence of adversarial responses. The thesis provides the analytical tools necessary to conduct such analysis in contested environments where traditional methods fail due to interference effects and strategic interdependence.

In summary, this dissertation makes the following contributions to both scientific knowledge and societal understanding of complex security contexts:

- **Insights**: Adaptation of causal inference concepts through the clarification of underlying assumptions and the integration of strategic elements. This provides the basis for the formalization of strategic causal concepts, which are essential for reasoning in complex security environments.
- **Techniques**: Development of computational methods for approximating optimal causal interventions in hybrid Bayesian networks through discretization and knowledge compilation. This enables applications of causal inference tools in resource-constrained security environments.
- **Applications**: Empirical demonstrations of causal frameworks in complex security contexts through environmental conflict analysis in Iraq, addressing interference, and hybrid threat deterrence modeling, incorporating strategic interaction. These cases demonstrate the policy relevance of the proposed methods.

1.3 Outline

The research questions are addressed across different chapters of this dissertation, which is structured as follows. Chapter 2 introduces key preliminaries in probability theory, graph theory, and game theory. Chapter 3 disentangles fragmented research on causality by mapping core concepts onto Pearl's causal hierarchy. This provides practitioners with a structured framework for selecting appropriate methods aligned with

the level of causal inquiry they seek to address, while making explicit the assumptions each level entails. In doing so, the chapter responds to RQ1.1 and RQ1.2. Chapter 4 addresses RQ1.3 by bringing together scattered research on (causal) game-theoretical concepts and providing a structured guide to their application for practitioners. Chapter 5 presents the methodological contribution of this research and addresses RQ2 by introducing a computationally efficient method for optimizing causal interventions. Specifically, it includes the introduction of an efficient causal inference method, supported by empirical validation of its accuracy and computational efficiency. Additionally, a technique for integrating this method into an optimization framework for multiple causal interventions is proposed. In Chapter 6, RQ3 is addressed through the application of the previously introduced concepts to case studies in environmental conflict and hybrid threats. Finally, Chapter 7 presents the concluding remarks and future research directions.

1.4 Publications of the Thesis

All but one of the studies presented in this thesis have been published in reputable peer-reviewed journals and conference proceedings, reflecting the scholarly contribution and relevance of the work. The remaining paper is currently under peer review. The contents of this thesis consist of the following papers.

[251] Maarten C Vonk, Ninoslav Malekovic, Thomas Bäck, and Anna V Kononova. Disentangling causality: assumptions in causal discovery and inference. *Artificial Intelligence Review*, 56(9):10613–10649, 2023.

[252] Maarten C Vonk, Mauricio Gonzalez Soto, and Anna V Kononova. Graphical models for decision-making: Integrating causality and game theory. *arXiv preprint arXiv:2504.13210*, 2025.

[249] Maarten C Vonk, Sebastiaan Brand, Ninoslav Malekovic, Thomas Bäck, Alfons Laarman, and Anna V Kononova. Balancing computational cost and accuracy in inference of continuous bayesian networks. In *International Conference on Probabilistic Graphical Models*, pages 361–381. PMLR, 2024.

[253] Maarten C Vonk, Diederick Vermetten, Jacob de Nobel, Sebastiaan Brand, Ninoslav Malekovic, Thomas Bäck, Alfons Laarman, and Anna V Kononova. Optimizing causal interventions in hybrid bayesian networks. In *International Conference on Information Processing and Management of Uncertainty in Knowledge-Based Systems*, pages 245–256. Springer, 2024.

[250] Maarten C Vonk, Anna V Kononova, Thomas Bäck, and Tim Sweijs. Multi-agent influence diagrams to hybrid threat modeling. *The Journal of Defense Modeling and Simulation*, 0(0), 2025.

[154] Ninoslav Malekovic, Maarten C Vonk, Laura Birkman, Tim Sweijs, Anna V Kononova, and Thomas Bäck. Applying causality to environmental security in Iraq. *Scientific Reports*, 15(1):16198, 2025.