Three Essays on Institutional Design and the Provision of Public Goods

---

Zur Erlangung des akademischen Grades eines

Doktors der Wirtschaftswissenschaften (Dr. rer. pol.)

von der KIT-Fakultät für Wirtschaftswissenschaften
des Karlsruher Instituts für Technologie (KIT)
genehmigte

Dissertation

von
M. Sc. Resul Zoroğlu

Erstgutachterin:	Prof. Dr. Ingrid Ott
Zweitgutachter:	Prof. Dr. Utku Ünver
Tag der mündlichen Prüfung:	25. September 2025
Karlsruhe	(2025)

Man is by nature a social being and necessarily depends on cooperation with others to secure his existence, for he cannot achieve his essential needs alone. […] Through cooperation, the needs of a number of persons, many times greater than their own number, can be satisfied.

Ibn Khaldūn (1332–1406), *The Muqaddimah*

To my wife Dilara

A Personal Reflection

When I was four years old, many people in my environment worked in the low-wage sector—cleaning kitchens, working in catering, or taking orders at fast food restaurants, where everything was greasy. Some worked with a smile on their faces and greeted everyone with a friendly "hello." At that age, I believed we lived in a world where everyone earned the same salary, because anything else would have been unfair. That's why I wanted to become like the happy man: I wanted to do the job of those who seemed the happiest.

This early sense of justice was rooted in an idea of equality I was taught from a young age: fairness meant equal treatment for all. Over time, however, I came to understand that this view was incomplete. Fairness is not always equality; it may also require recognizing the differences in mental and physical effort, responsibility, or contribution. Equal pay for unequal work may itself be unjust.

Later, as a high school student, I set myself a new goal: I wanted to become a doctor, to help those who couldn't afford medical care. However, in economics class, I discovered something unexpected: a fascination with how societies allocate resources and how small institutional changes can lead to significant improvements in people's lives on a large scale. It became clear to me that economic policies—such as interest rate adjustments, tax incentives, and redistribution mechanisms—can have a profound impact on social outcomes. I began to believe that I might help more people through economic insight than through medical care.

That realization was a turning point. It taught me that systemic change can sometimes be more powerful than individual treatment. To contribute meaningfully, however, I understood I had to grow—both intellectually and personally. I needed to deepen my understanding of institutions, incentives, and justice, and to refine the tools I would use to analyze them.

This dissertation is part of that journey. The dissertation examines how institutions can be designed to provide public goods—those services and protections that benefit all of us, yet are often taken for granted. Each of the three papers engages with this theme from a different angle, combining theory and empirics to explore how supranational cooperation, defense burden-sharing, and crowdfunding mechanisms can be structured to improve outcomes and enhance fairness.

In doing so, I return to a simple childhood aspiration: to make a difference in people's lives—only now, not by the job of those who seemed the happiest or practicing medicine, but by contributing to a better understanding of how we can design fairer and more effective economic institutions.

Abstract

In this thesis, we study three distinct approaches to the provision of public goods in supranational and decentralized contexts. The thesis comprises three self-contained research papers that address fundamental challenges in international cooperation, burden sharing, and incentive-compatible redistribution.

The first paper develops formal stability conditions for coalition structures using a behavioral economic approach grounded in game-theoretic tools. The model is validated with real-world data on supranational public goods and delivers both explanatory and predictive power. The analysis is initially limited to supranational public goods where tasks, once carried out at external borders, become redundant within national boundaries. Applied to the European Sky Shield Initiative (ESSI), the model predicts partial cooperation patterns consistent with recent political developments.

The second paper empirically re-examines the distribution of benefits within coalitions. The analysis builds on established methods from the NATO burden-sharing literature, specifically Spearman rank and Wilcoxon signed-rank tests, and focuses on European NATO members. We construct a statistically validated average benefit share measure based on GDP, population and proximity to Russian borders. The resulting metric aligns more closely with observed burden allocations and offers a more accurate benchmark than conventional indicators.

The third paper investigates how surplus should be redistributed in the provision of public goods. Using an axiomatic approach, we identify fundamental limitations in the design of rebate rules by demonstrating the impossibility of simultaneously satisfying participation incentives, contribution incentives, and a fairness criterion. To address this tension, we propose a new redistribution rule which satisfies a weaker version of these axioms while preserving meaningful fairness and incentive properties: the Proportional Rebate with Threshold (PRT) rule. We show that the PRT rule generates higher redistributions when an individual increases contributions. We argue this strengthens the incentive to contribute.

Together, these papers contribute to a deeper theoretical and empirical understanding of how collective action problems can be mitigated through tailored institutional design, combining behavioral, empirical and axiomatic approaches.

Zusammenfassung

In dieser Dissertation untersuche ich drei unterschiedliche Ansätze zur Bereitstellung öffentlicher Güter in supranationalen und dezentralen Kontexten. Die Dissertation umfasst drei eigenständige wissenschaftliche Arbeiten, die grundlegende Herausforderungen internationaler Kooperation, gerechter Lastenteilung und anreizkompatibler Rückverteilung adressieren.

Die erste Arbeit entwickelt formale Stabilitätsbedingungen für Koalitionsstrukturen auf Grundlage eines verhaltensökonomischen Ansatzes unter Verwendung spieltheoretischer Werkzeuge. Das Modell wird anhand von Daten zu supranationalen öffentlichen Gütern validiert und zeigt sowohl Erklärungs- als auch Prognosekraft. Im Fokus stehen supranationale öffentliche Güter, bei denen Aufgaben, die einmal an der Außengrenze erbracht werden, innerhalb nationaler Grenzen redundant sind. Angewandt auf die European Sky Shield Initiative (ESSI) prognostiziert das Modell eine partielle Kooperation, die mit aktuellen politischen Entwicklungen übereinstimmen.

Die zweite Arbeit untersucht empirisch die Verteilung von Nutzen innerhalb von Koalitionen. Aufbauend auf etablierten Verfahren aus der NATO-Lastenteilungsliteratur – insbesondere Spearman-Rangkorrelationen-Test und Wilcoxon-Vorzeichen-Rang-Tests – richtet sich die Analyse auf die europäischen NATO-Mitgliedstaaten. Auf dieser Basis wird ein statistisch validiertes Maß für den durchschnittlichen Nutzenanteil entwickelt, das auf BIP, Bevölkerungsgröße und geografischer Nähe zur russischen Grenze basiert. Diese Metrik korrespondiert mit den beobachteten Verteidigungslasten als herkömmliche Indikatoren und bietet somit einen präziseren Referenzwert für den durchschnittlichen Nutzenanteil.

Die dritte Arbeit befasst sich mit der Frage, wie Überschüsse bei der Bereitstellung öffentlicher Güter rückverteilt werden sollten. In einem axiomatischen Ansatz identifizieren wir grundlegende Grenzen bei der Gestaltung von Rückzahlungsregeln, indem wir ein Unmöglichkeitstheorem formulieren: Es ist nicht möglich, Teilnahmeanreize, Beitragsanreize und ein Fairnesskriterium gleichzeitig vollständig zu erfüllen. Um diesen Zielkonflikt zu entschärfen, schlagen wir eine neue Rückverteilungsregel vor, die abgeschwächte Versionen dieser Axiome erfüllt und zugleich zentrale Fairness- und Anreizeigenschaften wahrt: die „Proportional Rebate with Threshold“ (PRT) Regel. Wir zeigen, dass die PRT-Regel bei steigenden Beiträgen zu höheren Rückzahlungen führt als gängige Rückverteilungsregeln. Dieses Verhalten stärkt aus unserer Sicht die Anreize zum Beitragen.

Gemeinsam leisten diese drei Arbeiten einen Beitrag zu einem vertieften theoretischen und empirischen Verständnis dafür, wie kollektive Handlungsprobleme durch gezieltes institu-

tionelles Design abgemildert werden können – im Zusammenspiel verhaltensökonomischer, empirischer und axiomatischer Ansätze.

Achknowledgments

I would like to thank my supervisor, Ingrid Ott, who welcomed me as a PhD student at KIT. Over the past three years, Ingrid has granted me the freedom to pursue my academic development while consistently offering critical and constructive feedback whenever it was needed. I am equally grateful to my second advisor, Utku Ünver, who welcomed me at Boston College, where I had the privilege of spending seven months. His intellectual depth and openness to interdisciplinary exchange have broadened my perspective.

A special thanks goes to Tayfun Sönmez, whose course provided an exceptionally enriching academic experience. I also thank the people at Boston College for their warm hospitality, the lively academic discussions, and the inspiring atmosphere that made my time there truly memorable.

I am especially grateful to Cyril Rouault for the close academic collaboration. I am very glad to have met you at Boston College. My collaboration with Jonathan Völkle has been equally inspiring; together, we brought creativity, analytical rigor, and exceptional dedication to our joint projects. My thanks also go to Noah Oerther for our collaboration, in which we complemented each other as a strong and well-coordinated team.

In this same spirit, I would like to thank Nikas Scheidt, Narek Mirzoyan, Martha Loewe, Menna Ghoniem, and Ramona Bodemer for the enriching time we spent together at the institute—for the conversations, the insights, and the sense of shared purpose.

My sincere thanks go to the Avicenna-Studienwerk e.V., funded by the German Federal Ministry of Education and Research, which supported me throughout my doctoral studies both intellectually and financially, and in particular made my research stay at Boston College possible. I also thank the Graduate School Cultures of Knowledge (CuKnow) at KIT for funding my participation in conferences and other academic initiatives.

A special thank-you goes to my friends from Baden-Baden, Karlsruhe, and the surrounding area. Each of you supported me in your own way and inspired me during key moments of this journey.

I am deeply grateful to my parents, Necla and Ferhat Zoroğlu, for their unconditional love and support. Both of them built a new life from the ground up—far from their homeland, family, and familiar surroundings—with courage, perseverance, and unwavering determination. Their ambition to provide a better life for their children, and their heartfelt and exemplary character, have left a lasting impression on me.

To my siblings, Ekrem, Esma, and Emirhan, thank you for your trust, your encouragement, and your steady presence throughout all stages of my doctoral journey. I also thank my

parents-in-law, Canan and Bayram Çatlı, for their constant support and the trust they have placed in me.

And last—but with all my heart—I thank my soulmate and wife. You have accompanied me on this entire journey, from the very beginning to the completion of this work. You have always stood by my side and never stopped believing in me. The best decision I made during my PhD was not an academic one—it was marrying you.

Danksagung

Einen besonderen Dank möchte ich meiner Erstbetreuerin Ingrid Ott aussprechen, die mich als Doktoranden am KIT aufgenommen hat. In den letzten drei Jahren hat mir Ingrid die Freiheit zur wissenschaftlichen Entfaltung gegeben und mir stets kritische Impulse vermittelt, wann immer sie nötig waren. Ebenso danke ich meinem Zweitbetreuer Utku Ünver, der mich am Boston College aufgenommen hat und bei dem ich sieben prägende Monate verbringen durfte. Seine intellektuelle Tiefe und Offenheit für interdisziplinären Austausch haben meine Perspektiven erweitert.

Ein besonderer Dank gilt Tayfun Sönmez, dessen Kurs einen außergewöhnlich wertvollen Austausch ermöglichte. Ebenso danke ich den Doktoranden am Boston College, für das Miteinander, den regen fachlichen Austausch und die inspirierende Atmosphäre, die diese Zeit zu einer außergewöhnlichen Erfahrung gemacht haben.

Cyril Rouault danke ich für die enge wissenschaftliche Zusammenarbeit und bin sehr froh, dich am Boston College kennengelernt zu haben. Mit Jonathan Völkle verbindet mich eine inspirierende Kooperation, in der wir Kreativität, analytische Schärfe und außergewöhnliche Arbeitsbereitschaft vereint haben. Mein Dank gilt auch Noah Oerther, für die gemeinsame Zusammenarbeit, in der wir uns als starkes und gut eingespieltes Team ergänzen konnten.

In diesem Atemzug möchte ich Nikas Scheidt, Narek Mirzoyan, Martha Loewe, Menna Ghoniem und Ramona Bodemer für die bereichernde gemeinsame Zeit am Institut danken – für Gespräche, Impulse und ein wertvolles Miteinander.

Mein aufrichtiger Dank gilt dem Avicenna-Studienwerk e.V., gefördert vom Bundesministerium für Bildung und Forschung, das mich während meiner Promotion sowohl ideell als auch finanziell unterstützt und insbesondere meine Forschungsreise ans Boston College ermöglicht hat. Auch der Graduate School Cultures of Knowledge (CuKnow) am KIT danke ich herzlich für die finanzielle Förderung im Rahmen von Konferenzen und wissenschaftlichen Vorhaben.

Ein besonderer Dank gilt meinen Freunden aus Baden-Baden, Karlsruhe und Umgebung. Jeder Einzelne von euch hat mich auf seine Weise begleitet, unterstützt und in entscheidenden Momenten inspiriert.

Meinen Eltern, Necla und Ferhat Zoroğlu, danke ich für ihre bedingungslose Unterstützung und Liebe. Beide haben fern der Heimat, getrennt von Familie und vertrauter Umgebung, hier ein neues Leben aufgebaut – von Grund auf, mit Mut, Ausdauer und unbeirrbarem Willen. Ihr Ehrgeiz, uns Kindern ein besseres Leben zu ermöglichen, und euer herzhafter, vorbildlicher Charakter haben mich tief geprägt. Meinen Geschwistern Ekrem, Esma und

Emirhan danke ich für ihr Vertrauen, ihren Rückhalt und ihre geduldige Begleitung in allen Phasen meiner Promotion. Meinen Schwiegereltern, Canan und Bayram Çatlı, danke ich für ihre stets offene und herzliche Unterstützung sowie für das Vertrauen, das sie mir entgegenbringen.

Und zuletzt – aber mit ganzem Herzen – danke ich meiner Seelenverwandten und Ehefrau. Du hast mich vom ersten Moment an auf dieser Reise begleitet. Die beste Entscheidung während meiner Promotion war nicht wissenschaftlicher Natur: Es war, dich zu heiraten.

Contents

1 General Introduction **1**

1.1 Motivation and Fundamental Concepts 1

1.2 Background 6

1.3 Extension to Chapter 2 8

1.4 Extension to Chapter 4 10

2 The Provision of Supranational Public Goods **15**

2.1 Introduction 15

2.2 Related Literature 16

2.3 A Model of the Provision of Supranational Public Goods 18

2.3.1 Formal Description of the Game 18

2.3.2 Underlying Framework of the Model 23

2.3.3 The Model 25

2.4 Application to European Sky Shield Initiative 27

2.4.1 A Short History of the ESSI 28

2.4.2 No Stable Coalition 29

2.4.3 Stable Coalition 30

2.4.4 Data Input for the Stable Coalition: ESSI Framework Expanded to Include Italy and France 31

2.4.5 Analysis of the Stable Coalition: ESSI Framework Expanded to Include Italy and France 34

2.5 Conclusion and Outlook 36

Appendix A The Provision of Supranational Public Goods **39**

A.1 Illustrative Example for a Stable Coalition for Selected Threat Factors with Belgium, Germany and the Netherlands 39

A.1.1 Case: $\alpha_0 = 1$ 41

A.1.2 Case: $\alpha_0 = 1.282$ 46

A.1.3 Case: $\alpha_0 = 1.332$ 49

A.1.4 Case: $\alpha_0 = 1.349$ 52

A.2 Wilcoxon Signed-Rank Test 55

A.3 Data: ME and GDP (2022) 57

A.4 Alternative Burden-Sharing and Sensitivity Analysis 59

A.5 Application to ESSI (GDP) 60
A.6 Application to ESSI (ME) 65
  A.6.1 Detailed Analyses 65
  A.6.2 Additional Analyses 67
  A.6.3 Scenario: 'Distance Category' 70
A.7 Albania and Portugal Join ESSI as of February 2025 74
  A.7.1 Application to ESSI (ME) as of February 2025 74
  A.7.2 Application to ESSI (GDP) as of February 2025 78
  A.7.3 Scenario: 'Distance Category' as of February 2025 80

3 European NATO Burden Sharing 1993-2022 **85**
3.1 Introduction 85
3.2 Related Literature 87
3.3 Data and Methods 89
3.4 Ability to Pay and Burden Sharing 91
  3.4.1 NATO 91
  3.4.2 European NATO 94
3.5 The Concordance between Defense Burdens and Benefit Shares 96
  3.5.1 European NATO 96
  3.5.2 Comparison to NATO 104
3.6 Concluding Remarks 105

Appendix B European NATO Burden Sharing 1993-2022 **107**
B.1 Illustrative Example of the Wilcoxon Signed-Rank Test 107
B.2 Past Empirical Record 108
B.3 European NATO Distance Categories 111
B.4 Evolution of Defense Burden and Average Benefit Share 2 across European NATO 112
B.5 Average Benefit Shares from 1993-2022 113
B.6 The Concordance between Defense Burdens and Benefit Shares in NATO 129
B.7 Robustness Checks: Alternative Weighting of Benefit Shares 144
  B.7.1 European NATO 144
  B.7.2 NATO 149

4 Designing Rebate Rules in Public Goods Provision **155**
4.1 Introduction 155
4.2 Related Literature 157
4.3 Model 158
  4.3.1 Redistribution Problem 158
  4.3.2 Axioms 158
4.4 Limits on Rebate Rules 160

4.5 Proportional Rebate with Threshold Rule and Axioms 161
4.6 Comparison of Rebate Rules 164
4.7 Concluding Remarks 169

Appendix C Designing Rebate Rules in Public Goods Provision 171
C.1 Additional Analysis 171
C.2 Proofs 172
C.2.1 Proof of Theorem 1 172
C.2.2 Proof of Theorem 2 172
C.2.3 Proof of Theorem 3 172
C.2.4 Proof of Theorem 4 172
C.2.5 Proof of Theorem 5 173

5 Conclusion 179

A Tale of Neighbors, Cooperation and a Streetlight 183

Bibliography 187

Declaration 197

Curriculum Vitae 199

List of Figures

1.1 Structure of the Dissertation . . . 5

2.1 European Sky Shield Initiative Map . . . 28
2.2 Treemap GDP and ME of European NATO . . . 32
2.3 Contributions and Payoffs by Country ($\alpha_0 = 7.75$) . . . 36

A.1 Normal Form: Belgium, Germany, and the Netherlands ($\alpha_0 = 1.000$) . . . 45
A.2 Normal Form: Belgium, Germany, and the Netherlands ($\alpha_0 = 1.282$) . . . 48
A.3 Normal Form: Belgium, Germany, and the Netherlands ($\alpha_0 = 1.332$) . . . 51
A.4 Normal Form: Belgium, Germany, and the Netherlands ($\alpha_0 = 1.349$) . . . 54
A.5 Average Benefit Share and Input Determinants (GDP) . . . 64
A.6 Average Benefit Share and Input Determinants (ME) . . . 68
A.7 Threshold Threat Levels by Country (Exposed Border with Russia) . . . 69
A.8 Average Benefit Share and Input Determinants (Distance Category) . . . 72
A.9 Threshold Threat Levels by Country (Distance Category) . . . 73
A.10 Contributions and Payoffs by Country ($\alpha_0 = 6.385$) . . . 77

3.1 Defense Burden and Average Benefit Share (ABS 4) European NATO . . . 103
3.2 Comparison: ABS (ABS 4) and Defense Burden of European NATO (France, Germany, and the United Kingdom) and NATO (US) . . . 104

B.1 Defense Burden and Average Benefit Share (ABS 2) European NATO . . . 112

4.1 Illustration of Available Surplus . . . 161
4.2 Redistribution Outcomes under PRT, Shapley, and PR Rules across Five Cases 168
4.3 Redistribution Outcomes in Case 1 and Case 3 under PRT, Shapley, and PR Rules . . . 169

C.1 Redistribution Outcomes in Case 2, Case 4 and Case 5 under PRT, Shapley, and PR Rules . . . 171

List of Tables

2.1 Fiction Example: Stable Coalition Structure with Three Players 22

2.2 Conditions for a Stable Coalition Structure with 15 Countries out of a 35-Country Set 29

2.3 Stable Coalition Scenarios for Different Configurations with 35 Countries . . 30

2.4 Conditions for a Stable Coalition in the ESSI with Italy and France among 35 Countries 30

2.5 Key Indicators of ESSI Countries (22 Members plus Italy and France) in a 35-Country Set 33

2.6 Determinants, Benefit Shares, and Payoffs for 24 Participants in a Stable Coalition with 35 Countries ($\alpha_0 = 7.75$) 35

A.1 Example: Absolute and Relative Values of Belgium, Germany, and the Netherlands 40

A.2 Example:Conditions for a Stable Coalition Belgium, Germany, and the Netherlands ($\alpha_0 = 1.000$) 44

A.3 Example: Conditions for a Stable Coalition Belgium, Germany, and the Netherlands ($\alpha_0 = 1.282$) 47

A.4 Example: Conditions for a Stable Coalition Belgium, Germany, and the Netherlands ($\alpha_0 = 1.332$) 50

A.5 Example: Conditions for a Stable Coalition Belgium, Germany, and the Netherlands ($\alpha_0 = 1.349$) 53

A.6 Wilcoxon Signed-Rank Correlation of ME/European NATO ME and Alternative Average Benefit Shares 55

A.7 Wilcoxon Signed-Rank Correlation of ME/European NATO ME and Single Benefit Shares 56

A.8 Military Expenditure and GDP for ESSI Members and Non-Members 57

A.9 Conditions for Stable Coalition Structures of Different Sizes in a 35-Country Set 61

A.10 Stable Coalition Scenarios for Different Configurations with 35 Countries (GDP) 61

A.11 Key Indicators of ESSI Countries (22 Members plus Italy and France) in a 35-Country Set (GDP) 62

A.12 Detailed Stable Coalition Conditions for ESSI with Italy and France within 35 Countries . . . 66
A.13 Conditions for Stable Coalition Structures of Different Sizes in a 35-Country Set . . . 67
A.14 Stable Coalition Scenarios for Different Configurations with 35 Countries (ME) 67
A.15 Key Indicators of ESSI Countries (22 Members plus Italy and France) in a 35-Country Set (DC) . . . 70
A.16 Stable Coalition Scenarios for Different Configurations with 35 Countries 2025 (GDP) . . . 74
A.17 Determinants, Benefit Shares, and Payoffs for 25 Participants in a Stable Coalition with 35 Countries 2025 ($\alpha_0 = 6.385$) . . . 75
A.18 Key Indicators of ESSI Countries (23 Members plus Italy and France) in a 35-Country Set 2025 . . . 76
A.19 Stable Coalition Scenarios for Different Configurations with 35 Countries 2025 (GDP) . . . 78
A.20 Key Indicators of ESSI Countries (23 Members plus Italy and France) in a 35-Country Set 2025 (GDP) . . . 78
A.21 Key Indicators of ESSI Countries (23 Members plus Italy and France) in a 35-Country Set 2025 (DC) . . . 80

3.1 Spearman Rank Correlation Between Defense Burden (ME/GDP) and GDP in NATO . . . 93
3.2 Spearman Rank Correlation Between Defense Burden (ME/GDP) and GDP in European NATO . . . 95
3.3 Wilcoxon Signed-Rank Correlation of ME/European NATO ME and Alternative Average Benefit Shares . . . 99
3.4 Wilcoxon Signed-Rank Correlation of ME/European NATO ME and Single Benefit Shares . . . 101

B.1 Illustrative Application of Wilcoxon Signed-Rank Test . . . 107
B.2 Military Expenditures as a Share of Gross Domestic Product (GDP) . . . 109
B.3 European NATO Countries by Distance Category to Russia . . . 111
B.4 Defense Burden and Average Benefit Share 4 in European NATO . . . 113
B.5 Defense Burden and Average Benefit Shares 1-3 in European NATO for Selected Years (1995, 2000, 2005, 2010, 2015, 2020) . . . 119
B.6 Defense Burden and Average Benefit Shares 1-3 in European NATO . . . 121
B.7 Defense Burden and Average Benefit Shares 1-4 in NATO for Selected Years (1995, 2000, 2005, 2010, 2015, 2020) . . . 130
B.8 Wilcoxon Signed-Rank Correlation of ME/NATO ME and Alternative Average Benefit Shares . . . 132
B.9 Wilcoxon Signed-Rank Correlation of ME/NATO ME and Single Benefit Shares . . . 133

B.10 Defense Burden and Average Benefit Shares 1-4 in NATO 134
B.11 Wilcoxon Signed-Rank Correlation of ME/European NATO ME and GDP-Focused Average Benefit Shares 146
B.12 Wilcoxon Signed-Rank Correlation of ME/European NATO ME and Population-Focused Average Benefit Shares 147
B.13 Wilcoxon Signed-Rank Correlation of ME/European NATO ME and Threat-Focused Average Benefit Shares 148
B.14 Wilcoxon Signed-Rank Correlation of ME/NATO ME and GDP-Focused Average Benefit Shares 150
B.15 Wilcoxon Signed-Rank Correlation of ME/NATO ME and Population-Focused Average Benefit Shares 151
B.16 Wilcoxon Signed-Rank Correlation of ME/NATO ME and Threat-Focused Average Benefit Shares 152

4.1 Comparison of Redistribution Outcomes for Case 1 165
4.2 Comparison of Redistribution Outcomes for Case 2 166

Acronyms and Abbreviations

ABS	Average Benefit Share
AoN	All or Nothing
B	Billion
Bosnia & Herz.	Bosnia and Herzegovina
CIA	Central Intelligence Agency
CM	Contribution Monotonicity
DB	Defense Burden
DC	Distance Category
EB	Exposed Border
eb	equally weighting border
EBR	Exposed Border with Russia
ed	equally weighting distance category
EDF	European Defense Fund
ESSI	European Sky Shield Initiative
ETE	Equal Treatment of Equals
EU	European Union
FD	Full Distribution
FSR	Full Surplus Redistribution
GDP	Gross Domestic Product
KiA	Keep it All
ME	Military Expenditure
MEADS	Medium Extended Air Defense System

MNP	Monotonicity Net Payment
MRC	Marginal Rebate of Contribution
NATO	North Atlantic Treaty Organization
N. Macedonia	North Macedonia
PESCO	Permanent Structured Cooperation
POP	Population
PR	Proportional Rebate
PRT	Proportional Rebate with Threshold
PSR	Partial Surplus Redistribution
RAND	RAND Corporation (Research and Development)
R&D	Research and Development
SC	Stable Coalition
SIPRI	Stockholm International Peace Research Institute
Strong-C	Strong Consistency
ub	unequally weighting border
ud	unequally weighting distance category
UK	United Kingdom
US	United States
VCG	Vickrey–Clarke–Groves Mechanism
Weak-C	Weak Consistency
Weak-CM	Weak Contribution Monotonicity
WWII	World War II

Chapter 1

Chapter 1

General Introduction

1.1 Motivation and Fundamental Concepts

Economics is the study of the *efficient use of scarce resources*. People need resources to fulfill their *wants*. Because resources are scarce, people make decisions about how to use them (Robbins, 1932; Mankiw, 2020). Every day, individuals make choices about the use of their own resources—for example, what to eat for lunch. The decision whether to eat lunch in an upscale restaurant or a cafeteria depends on personal preferences and one's budget. Most often, one asks: *"How much am I willing to pay for the good or service?"*

To understand why one is willing to pay more for some goods than for others, we must take a closer look at the goods themselves. Goods can be divided into private and public goods.[1] This distinction is based on the concepts of *rivalry* and *excludability*.

Rivalry refers to the idea that if one person uses a good, another person cannot use it at the same time. For example, if one person orders a plate of pasta in a restaurant, no other person can eat from it without reducing the portion available to the one who ordered it. *Rivalry* also applies to something one buys that no one else can buy in exactly the same form. To clarify: even a hammer in a household is rivalrous, since only one person can use it at a time—even if, unlike the pasta, it is not consumed.

Excludability is the concept that others can be actively prevented from using a good. A common example is putting up a fence around one's garden to keep others out.

Goods that are both *rivalrous* and *excludable* are called *private goods*. A plate of pasta in a restaurant is a private good.

Goods that are *non-rivalrous* and *non-excludable* are called *public goods*. An example is street lighting. Street lighting is *non-excludable* because individual consumption cannot be prevented. It is also *non-rivalrous* because one person's use of the light does not diminish the benefit for others. Street lighting is available to everyone, regardless of their contribution. The good is *non-excludable* because no one walking down the street can be excluded from its benefits, and it is (more or less) *non-rivalrous* because each person benefits from it without reducing others' utility. People may nevertheless hold different valuations of the same good, which leads to differing *willingness to pay* for its provision, or people may even underreport their true *willingness to pay* to avoid bearing the cost (Samuelson, 1954).[2]

---

[1] Other commonly discussed types include club goods (excludable but non-rivalrous) and common-pool resources (non-excludable but rivalrous).

[2] This foundational classification was first formalized by Samuelson (1954), who demonstrated that markets cannot efficiently provide public goods because individuals have an incentive to underreport their true willingness to pay, leading to underprovision.

As the name "public good" suggests, public goods are typically provided by the public sector, such as the state as provision occurs when the *sum of marginal benefits equals the marginal rate of transformation*, meaning, when each individual contributes to the cost in accordance with their preferences between public and private goods.[3] A further attribute of a public good is that society or the public benefits from its use. The example of street lighting in a neighborhood may serve as an illustration: everyone wants the light, though some residents benefit more than others (e.g., those who live closer). In a scenario with four neighbors, there are four parties who need to agree on how much each contributes to the cost. Everyone has an incentive to pay as little as possible for something useful, engaging in *free-riding* behavior—benefiting without contributing fully. This often leads to no provision at all, since no agreement can be reached—each person wants to minimize their own expense and hopes others will pay. As a result, the costs of the street lighting are not covered. At this point, the state intervenes, provides the lighting, and funds it through taxes.

This phenomenon is well known in economic theory. Society needs a state to overcome such market failures in terms of efficiency and fairness in resource allocation and distribution. Beyond private goods and services, public goods should be provided when their provision is socially desirable—even though the private sector lacks sufficient incentives.

In recent decades, a broad range of public goods has emerged. There is a general consensus that national public goods and services are fundamental to human well-being and that the state and the market must cooperate in their provision (Kaul et al., 1999). This is relatively straightforward in the *national* context.

In the *international* context, however, citizens first decide on their own national budgets, and only then must governments coordinate with other governments. Additionally, global public goods involve *externalities* that affect other countries. An example for an externality is the invention of an Ebola vaccine that benefits all countries, not just the inventor nation. In addition to the two well-known characteristics of public goods—*non-excludability* and *non-rivalry*—*global* public goods feature further attributes like the *range of spillovers* and *technology aggregation* (contribution to supply).

The discovery of a vaccine for Ebola, for instance, has a broader *range of spillovers* than a solution to a purely local problem (Arce M. and Sandler, 2002; Kanbur et al., 1999).

The relationship between individual contributions and the total quantity of a public good available for consumption is called *technology aggregation*—or more intuitively: *contribution to the available supply*. Technology aggregation indicates how the contribution of countries add up to a good that is then available for all. For example, total greenhouse gas emissions are the sum of emissions from all countries.[4] Likewise, the total of peacekeeping efforts is the sum of troops from all contributing countries. As with the example of funding street lighting, the *dominant strategy* for a country is to contribute no peacekeeping troops,

---

[3] However, public goods can also be (partially) provided by the private sector, especially when exclusion is feasible or incentives are aligned.

[4] The term "good" is used here in a neutral form. Greenhouse gas emissions can be classified as a "bad" due to their negative externalities.

regardless of what others do, because the individual cost outweighs the individual benefit. A higher-level actor among countries would be an international institution or a coordination mechanism, serving a role analogous to the relationship between citizens and the state in overcoming collective action problems inherent to public goods provision (Buchholz and Sandler, 2021; Sandler, 2004).

Institutions such as NATO or formal arrangements like the European Sky Shield Initiative (ESSI), emerge to mitigate free-riding, enforce contributions, and coordinate behavior (Sandler, 2004). Following North (1991), institutions are the "rules of the game"—formal or informal constraints that shape human behavior—with a normative and constructive element to design new ones that lead to desirable outcomes. From the perspective of *technology aggregation*, centralized or coordinated efforts are more efficient.[5] It is preferable that a technologically advanced country deflect an incoming comet from Earth—with the support of others—rather than having many countries attempt it unsuccessfully on their own.

To return to the *initial question* posed at the outset of this introduction:

What is each country or individual willing to pay for the provision of a public good—such as joint air defense or public parks?

This dissertation addresses this central question in three self-contained but thematically interconnected chapters, as visualized in Figure 1.1. Each chapter offers distinct theoretical and empirical contributions to understanding the institutional design of public goods provision, particularly in supranational contexts, international burden sharing, and redistribution mechanisms.

Chapter 2 develops a theoretical model of coalition formation for supranational public goods. Integrating insights from behavioral economics, the chapter develops the concept of stable coalition structures shaped by belief-restricted strategies (tacit binding). The model is then empirically applied to the European Sky Shield Initiative (ESSI), validating when and with whom stable coalitions can be achieved for joint air defense systems in Europe.

Chapter 3 provides an empirical reassessment of defense burden sharing among European NATO members over the period 1993–2022. The analysis evaluates whether the contributions of countries align with their benefits employing rank-based statistical methods. This chapter contributes to the broader understanding of burden-sharing in international alliances by extending and refining previous empirical assessments.

Chapter 4 shifts the focus to redistribution mechanisms within the provision of public goods, specifically in the context of crowdfunding environments. This chapter examines how alternative rebate rules impact fairness and incentive compatibility, offering an axiomatic approach and a comparative evaluation of various redistribution methods.

Overall, the dissertation advances our understanding of how institutions can effectively address coordination problems inherent in the provision of public goods, offering insights

---

[5] This efficiency advantage of centralization typically holds when transaction costs for coordination are low.

into policy implications for international cooperation and institutional design.

The remainder of the dissertation is structured as follows. Each chapter is self-contained and can be read independently, though they are unified by a common focus on the institutional design and the provision of public goods. General context and background on this overarching theme are provided in Section 1.2, *Background*. Chapter 2, *The Provision of Supranational Public Goods*, develops a behavioral game theoretic model of coalition formation for supranational public goods. Section 1.3 provides an extension to this chapter, containing additional supporting material. Chapter 3, *European NATO Burden Sharing 1993–2022*, provides an empirical investigation of defense spending patterns among European NATO members over three decades. Chapter 3 does not require further extension.[6] Chapter 4, *Designing Rebate Rules in Public Goods Provision*, examines mechanisms for redistributing surplus contributions in public goods provision. Section 1.4 provides an extension to this chapter, containing additional supporting material. Finally, Chapter 5, *Conclusion*, concludes the dissertation by reflecting on the common themes across the three works. An epilogue titled "A Tale of Neighbors, Cooperation and a Streetlight" follows and serves as an intuitive reflection on the central themes of this dissertation, inspired by the idea that the essence of complex problems can often be conveyed through simple stories—accessible to a broader audience.

---

[6] This chapter adopts an analytical framework that has been widely used in the literature, making the contribution easier to follow.

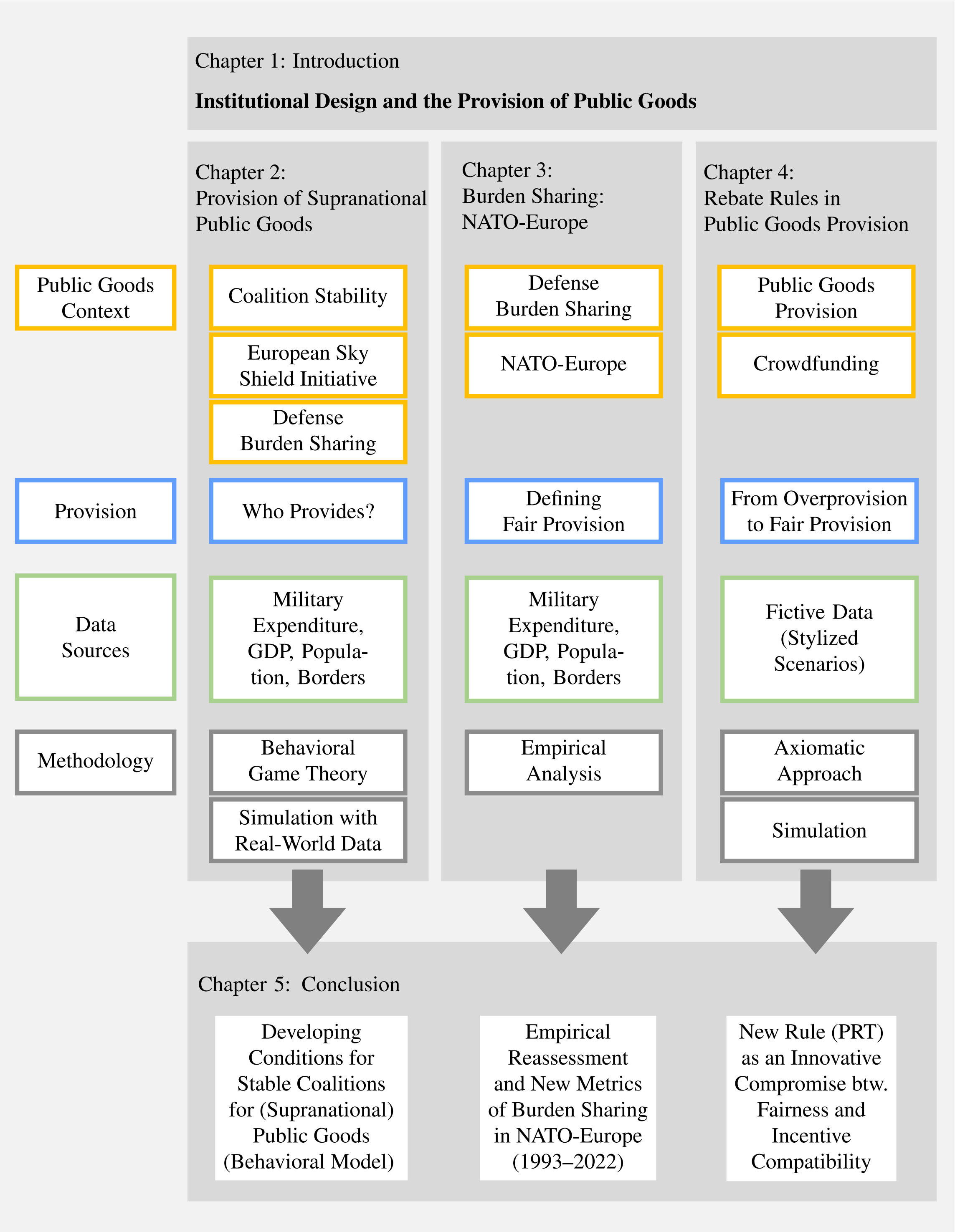


Figure 1.1: Structure of the Dissertation: Each chapter addresses a distinct aspect of public goods provision while maintaining thematic cohesion. The chapters offer contributions to the following topics: (i) coalition formation for supranational public goods, (ii) empirical burden-sharing within European NATO, and (iii) redistribution rules in crowdfunding.

1.2 | Background

In the following, we examine the background and historical development that explain why institutional design matters. We then discuss works that have made important contributions to the field of institutional design and the provision of public goods.

Historical Context.[7] In the 1960s, the world was marked by Cold War rivalry. On one side stood the Soviet Union with its model of centralized planning; on the other, the Western liberal democracies championed markets and decentralized decision-making, with economists like Friedrich Hayek leading the intellectual charge. The ideological contest was also an economic one—about how best to allocate scarce resources and deliver public goods. Hayek argued that markets were superior because they processed dispersed information better than any planner ever could. In his view, prices acted as signals, guiding millions of individual decisions in a way no central authority could replicate (Hayek, 1945).

But not everyone agreed it was so simple. Leonid Hurwicz, a Polish-Jewish immigrant to the United States who had escaped the rising authoritarianism of pre-Soviet Eastern Europe, saw a deeper issue: even if all information were available, would people share it truthfully? And what kinds of institutions would make self-interested behavior lead to good outcomes? These questions formed the foundations of what would later be called mechanism design theory (McGuire et al., 1972).

Hurwicz began with public goods, where free markets notoriously fail. The problem wasn't just about allocating goods efficiently, but about creating systems in which individuals would voluntarily contribute to something that benefits everyone (Hurwicz, 1973).

Around the same time, George Akerlof introduced the idea of adverse selection in markets with asymmetric information, showing that markets could fail even in competitive settings. Together, these contributions painted a more nuanced picture: markets work only when certain conditions hold—and when they don't, institutions matter (Akerlof, 1970).

In 2007, Leonid Hurwicz, Eric Maskin, and Roger Myerson were awarded the Nobel Prize in Economics "for having laid the foundations of mechanism design theory." Their work formalized the idea of institutional design and that public goods require mechanisms (Nobel Prize Outreach, 2007).[8]

Institutional Design. Mechanism design theory, as developed by Hurwicz and later extended by Maskin and Myerson, provides formal analytical tools to structure incentives systematically within intentionally designed institutional frameworks. Yet, institutional

---

[7] This narrative draws in part on material from the graduate course *Mechanism Design* (Econ 8819, Boston College), taught by Prof. M. Utku Ünver in 2025.

[8] For example: "Hurwicz's (1972) notion of incentive-compatibility can now be expressed as follows: the mechanism is incentive-compatible if it is a dominant strategy for each participant to report his private information truthfully."(Nobel Prize Outreach, 2007)

design extends beyond the scope of mechanism design alone. It must integrate broader considerations, including legitimacy, adaptation, and political feasibility, especially in international contexts where sovereignty and coordination challenges persist (Mendez, 1999; Goodin, 1996). Thus, institutional design can be viewed as a purposeful, strategic, and holistic approach to institutional creation or reform, explicitly aimed at overcoming coordination failures and sustaining cooperation in public goods contexts. At a foundational level, institutions can be understood in the sense of Douglass North's widely cited definition: "Institutions are the rules of the game in a society or, more formally, are the humanly devised constraints that shape human interaction" North (1991). These rules can emerge spontaneously, through evolutionary processes, or deliberately through intentional planning. In contrast, institutional design explicitly emphasizes the deliberate creation or adaptation of these rules to achieve specific outcomes. While institutions themselves may exist independently of intentionality—shaped by history, culture, and norms—institutional design presupposes agency, intentionality, and strategic reasoning. It involves carefully selecting, modifying, or crafting institutional arrangements to resolve incentive problems, encourage desired behaviors, and achieve collective goals, particularly in environments characterized by complex strategic interdependencies, information asymmetries, or conflicting interests. Complementing this formal view, Ostrom (1990) emphasized that effective institutions can also emerge from the bottom up, as self-organized systems rooted in trust, norms, and repeated interaction. Ostrom's work on common-pool resource management demonstrated that local communities can sustainably govern shared resources without relying solely on market mechanisms or top-down state intervention. Moreover, Goodin (1996) emphasizes that institutions are not always the result of deliberate, centralized planning by institutional "engineers." Many often emerge from overlapping, partial, or evolutionary processes. In this spirit, Sandler (2004) highlights that institutional design fundamentally alters the strategic environment of public goods provision. Through cost-sharing arrangements, joint-product inducements, or preference-revelation mechanisms, institutions can transform Public Goods Games from Prisoners' Dilemmas into Coordination Problems. Moreover, different aggregation technologies—such as summation, weakest-link, and best-shot—require distinct institutional forms. In each case, the goal of institutional design is to make cooperation rational, sustainable, and incentive-compatible.

These broader considerations are central to this dissertation. Designing institutions for the provision of public goods first requires an understanding of how individual actors benefit from the institution. Chapter 3 addresses this by examining the distribution of benefits across countries in the context of the European NATO, the NATO and the ESSI.

Second, it is essential to understand how strategic decisions are made and under what conditions stable cooperation arises—or fails to arise. Chapter 2 focuses on these questions by analyzing the behavior of actors within the ESSI.

Third, at the individual level, surplus redistribution of the jointly provided good becomes a key concern. Chapter 4 explores this issue by analyzing how rebate mechanisms allocate surplus among participants.

1.3 | Extension to Chapter 2

Chapter 2 develops a behavioral-economics framework for the provision of supranational public goods. We begin with a concise overview of how behavioral game theory has evolved. Following Gintis (2005) canonical classification, we map that evolution into five established stages. We then add a sixth, more recent stage introduced by Capraro (2013b), which, while not part of the original framework, appears to align conceptually and enrich the overall classification.

Stage 1: The Paradox Era. The Allais (1953) and Ellsberg (1961) paradoxes revealed systematic violations of expected-utility theory: decision makers appear to weight probabilities non-linearly. Allais received the 1988 Nobel Prize in Economics Sciences "for his pioneering contributions to the theory of markets and efficient utilization of resources"(Nobel Prize Outreach, 1988).

Stage 2: Market-Experiment Validation. Beginning in 1956, Vernon Smith ran controlled exchange experiments that reproduced competitive price equilibria with striking accuracy, thereby validating the rational, self-interested actor model rather than refuting it. Smith received the 2002 Nobel Memorial Prize in Economic Sciences for establishing "laboratory experiments as a tool in empirical economic analysis, especially in the study of alternative market mechanisms" (Nobel Prize Outreach, 2002b).

Stage 3: The Cognitive-Bias Program. Starting in the early 1970s Amos Tversky and Daniel Kahneman, and collaborators subjected classical decision theory to a battery of empirical tests. Their findings—prospect-theory (Kahneman and Tversky, 1979), hyperbolic discounting (Ainslie, George, 1992; Ahlbrecht and Weber, 1995; Laibson, 1997), regret theory (Robert, 1993), and more—mapped a landscape of predictable departures from standard rationality (Neumann and Morgenstern, 1944). Kahneman shared the 2002 Nobel Prize with Smith for "having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty"(Nobel Prize Outreach, 2002a).

Stage 4: Strategic-Interaction Anomalies. Ultimatum-game by Guth et al. (1982), bargaining studies by Roth et al. (1991); Kagel and Roth (1995), trust game Berg et al. (1995), and public-goods and common-pool experiments shifted the behavioral lens to explicitly strategic settings (Hayashi et al., 1999). Generous offers, and voluntary cooperation and other non-self-interested behavior of agents were initially treated as "irrational" deviations and flawed reasoning.

Stage 5: Modeling Social Preferences. In the next stage, fairness and reciprocity were no longer regarded as errors. Instead, other-regarding motives were embedded directly into utility functions while retaining the rational choice framework, thereby converting earlier "anomalies" into predicted behavior once agents were assumed to care about relative payoffs and the process of play (Fehr and Gächter, 2000; Bolton and Ockenfels, 2000; Charness and Rabin, 2002).

Stage 6: Anticipatory Strategic Reasoning. A more recent stream of research—sparked by Valerio Capraro's working paper *A Solution Concept for Games with Altruism and Cooperation* and further developed *A Model of Human Cooperation in Social Dilemmas*—asks: What if humans forecast "how social dilemmas evolves if they formed coalitions and then they act according to their most optimistic forecast" (Capraro, 2013a,b). Capraro observes that in one-shot social dilemmas (Prisoners' Dilemma, Public Goods, Traveler's Dilemma, etc.) players do not act as isolated utility-maximizers; instead, they imagine "what if we were a team?" and compare the payoffs of that hypothetical coalition with the temptation and risk of deviations.

Taken together, Capraro's forecast-based approach can be viewed as a sixth stage in behavioral game theory's evolution—one that blends the empirical focus of stages 1–5 with a normative aspiration: a formal rule that tells strategic, forward-looking players what it makes sense to do when they anticipate how the whole group might respond.

Like the five earlier stages, Capraro's framework is firmly rooted in experimental evidence on how people actually behave in social dilemmas.[9] In this view, cooperation arises not because payoffs are sweetened with altruism or because players make random errors, but because fully rational agents, mindful of how coalitions could form and how deviations might be punished.[10] Capraro leaves payoffs unaltered and assumes perfect calculation: cooperation emerges because players foresee the risks if they deviate and the gains if everyone cooperates. What changes is that each player anticipates how coalitions might form and how any defection could trigger retaliation.

This forecast-and-risk calculus allows the model to match several empirical regularities that puzzled earlier theories: higher cooperation rates in Prisoners' Dilemma as the benefit-to-cost ratio rises, lower claims in Traveler's Dilemma when the bonus/penalty grows, the hump-shaped contribution pattern in public goods games as groups expand, and the generous offers observed in ultimatum and dictator games.[11] In conclusion, Capraro blends the empirical orientation of behavioral game theory's first five stages with a clear normative proposition: cooperation can emerge from strategic reasoning under social anticipation alone (Capraro, 2013b).

---

[9] Earlier stages were driven by what people *do* in experiments and real life; Capraro goes further by proposing a rule that tells you what makes sense once you foresee others' responses.

[10] The downside risk if others subsequently deviate in response.

[11] Empirically, contributions trace an inverted-U: in very small groups they begin relatively low; as membership grows, average contributions rise because individuals see their cost share as reasonable and the public good as worthwhile; once the group passes a moderate size, additional members dilute each person's impact and heighten free-riding incentives, causing contributions to decline.

1.4 | Extension to Chapter 4

Economic theory has long grappled with the problem of free-riding in public goods provision. Samuelson (1954) established that individuals tend to under-contribute when the benefits of a public good are non-excludable, leading to inefficient provision. Warr (1983) introduced the neutrality theorem, positing that the total supply of a public good remains unchanged under income redistribution, provided the set of contributors remains the same. Bergstrom et al. (1986) expanded this argument by demonstrating that changes in the set of contributors could significantly impact public good provision, highlighting the importance of contribution incentives.

Threshold mechanisms have been proposed as solutions to the free-riding problem. Bagnoli and Lipman (1989) demonstrated that refund guarantees in voluntary contribution mechanisms could fully implement the core, ensuring that public goods are provided efficiently. Isaac et al. (1989) provided experimental evidence that refund guarantees increase contributions, while Bagnoli and Mckee (1991) found that withholding information about provision costs leads to contributions closer to individuals' true valuations. Provision Point Mechanisms (PPMs), such as those studied by Rondeau et al. (1999), reinforce this finding, showing that contributors are more willing to pledge when they are assured of a refund if the threshold is not met.[12] Zubrickas (2014) extended this concept by introducing refund bonuses, which serve as an ex-ante incentive to increase contributions in uncertain funding environments. However, these mechanisms primarily focus on pre-funding incentives rather than post-funding fairness, leaving open the question of how surplus funds should be managed once the provision point is reached.

A potential solution lies in rebate mechanisms. Marks and Croson (1998) and Spencer et al. (2009) distinguish between *refunds*, which apply when the funding goal is not met, and rebates, which redistribute excess contributions after the threshold is surpassed. Smith (1980) originally proposed a *proportional rebate* rule for public good auctions, and subsequent studies (Marks and Croson, 1998; Rondeau et al., 1999) introduced this concept into PPMs, demonstrating that proportional rebates can improve demand revelation. Spencer et al. (2009) tested multiple rebate mechanisms, including proportional, winner-take-all, and random full-rebate rules, concluding that proportional rebates were the most efficient at achieving funding goals while maintaining fairness. Liu et al. (2016) introduced the uniform price cap mechanism, which outperformed both no-rebate and proportional rebate models by increasing contributions and project realization rates. Recent research by Oezcelik et al. (2025) introduces the *Bid-Cap* Rule, which limits the highest individual contributions to prevent overpayment once the threshold is met.

Research on crowdfunding has also examined. Among the two dominant crowdfunding models, the all-or-nothing (AoN) model ensures that pledges are only collected if the funding goal is met, while the keep-it-all (KiA) model allows project creators to retain all contributions, even if the goal is not reached. Studies by Coats et al. (2009), Chemla and

---

[12] A real-life example is the Green Choice program run by Niagara Mohawk Power Company of New York. For details, see Marks and Croson (1998); Rose et al. (2002).

Tinn (2020), Cumming et al. (2020) find that AoN models generally lead to higher pledge amounts and greater project realization rates due. Despite the advantages of AoN, a significant challenge remains: when projects receive pledges that exceed the funding goal, how should excess contributions be handled? Traditional crowdfunding models do not explicitly address this issue, potentially leading to inefficient allocations or even deterring higher contributions. Béal et al. (2025) and Miglo (2022) emphasize the role of early backer incentives in enhancing funding success, with Béal et al. (2025) employing an axiomatic approach to characterize reward rules through natural fairness principles.

CHAPTER | 2

This part is based on the joint work:

The Provision of Supranational Public Goods: Application to the European Sky Shield Initiative,
by Resul Zoroğlu and Ingrid Ott.

ABSTRACT

This paper examines the provision of supranational public goods, such as airspace security, whose centralized provision reduces duplication across countries. We adopt a behavioral approach in which strategy profiles are restricted by beliefs—defined as the natural human inclination to cooperate by mentally simulating how coalitions might form if they act collectively and according to their most optimistic forecast—thereby inducing a form of tacit binding. We derive formal conditions for stable coalition structures, introduce a novel method for burden-sharing, and incorporate a threat factor that affects individual payoffs and, in turn, the formation of coalitions. This approach contrasts with the traditional view of public goods provision, which predicts non-cooperation in one-shot games. Our results are consistent with the recent developments of the European Sky Shield Initiative (ESSI), demonstrate the explanatory and predictive power, particularly in forecasting partial rather than full cooperation.

Chapter 2

The Provision of Supranational Public Goods

2.1 Introduction

In the wake of geopolitical shifts triggered by Russia's annexation of Crimea in 2014 and the subsequent large-scale invasion of Ukraine in 2022, European countries substantially increased their defense expenditures, reversing a prolonged trend of stagnation (European Commission, 2022). Notably, Germany emerged as a leader, allocating a special fund of €100 billion for defense, with €33.4 billion earmarked explicitly for air defense systems (Deutsche Bundesregierung, 2022).[1] To reduce inefficiencies associated with redundant national air defense systems and to strengthen collective defense capabilities, 14 NATO member countries and Finland initiated the European Sky Shield Initiative (ESSI) in October 2022, agreeing to coordinate multinational air defense.

The ESSI presents a significant deviation from traditional public goods theory. Germany emerged as the initiator of ESSI and demonstrated leadership, even though, based on its geographical position in Europe, it could free-ride, benefiting from the spillover effects of air defense systems provided by the easternmost countries that directly face the primary external threat. Instead, it appears as if the ESSI acts collectively.

To address such phenomena in the provision of supranational public goods[2] we combine two established theoretical frameworks: the approximation of the defense benefits of countries (Sandler and Forbes, 1980) and behavioral insights, demonstrating how individuals, guided by intrinsic motivations and optimistic expectations about collective action, tend toward cooperation in social dilemmas (Capraro, 2013a).

Sandler and Forbes (1980) examine various parameters that approximate countries' benefits over a period of time. Their analysis is based on the premise that countries will only spend as much as they benefit from doing so. In this context, the benefit refers to the (relative) utility, which should correspond to the relative military expenditures. Throughout their study, the weighted average of relative population, relative GDP, and relative exposed border length outside the NATO emerged a suitable measure for approximating utility, which they term the *Average Benefit Share* (ABS). (Sandler and Forbes, 1980; Khanna and Sandler, 1996, 1997; Sandler and Murdoch, 2000; Sandler and Shimizu, 2014; Cooper and Stiles, 2021; Bogers et al., 2022). We have implemented and modified this approximation

---

[1] The resources of the special fund are available beyond a single fiscal year and can be utilized according to demand.

[2] Accordingly, joint air defense is considered a supranational public good; however, some perspectives regard it as a global public good. Due to a Europe-wide air defense system, peace is maintained at least in the European region, or possibly even beyond, making people everywhere better off (Barrett, 2007).

by using the relative border length exposed to Russia as a factor in the weighting scheme. Sandler and Forbes (1980) approach explains the expense expenditure of countries based on their perceived benefits, it leaves open the question of why countries might cooperate beyond narrowly defined self-interest.

Insights from behavioral experiments provide a complementary perspective. Capraro (2013a) demonstrates that in certain social dilemmas, individuals behave as if they were acting collectively, even in one-shot public goods experiments where rational self-interest would predict otherwise (Isaac and Walker, 1988; Cooper et al., 1996; Goeree and Holt, 2001; Horton et al., 2011; Dreber et al., 2013). Classical approaches explain the tendency to cooperate by dividing people into pro-self and pro-social types (Liebrand, 1984; Liebrand et al., 1986; Kramer et al., 1986; Kuhlman et al., 1986; McClintock and Liebrand, 1988), by referring to forms of external control (Olson, 1965; Hardin, 1968; Dawes, 1980; Axelrod and Hamilton, 1981) or to long-term strategies in repeated social dilemmas (Isaac et al., 1984). Experimental evidence shows that the rate of cooperation in the same game depends on the respective payoffs, suggesting that people most likely practice some kind of indirect reciprocity (Nowak and Sigmund, 1998; Nowak, 2006) and that the same person may behave more or less cooperatively depending on the payoffs (Capraro, 2013a). Consequently, Capraro (2013a) suggests that individuals forecast how the game would be played if they formed coalitions.

In light of these insights, the question arises: How can cooperation in the provision of supranational public goods be explained and predicted? Addressing this question becomes imperative for refining our understanding of cooperative behavior and enhancing the effectiveness of models in capturing real-world scenarios.

Our key contribution is the characterization of conditions of a stable coalition structure, which we extend by integrating insights from behavioral economics—originally validated at the individual level—to predict strategic behavior at the level of sovereign countries. By linking the burden-sharing model (Sandler and Forbes, 1980) with the behavioral model (Capraro, 2013a), we develop a combined explanatory and predictive framework. This framework identifies stable coalition structures characterized by partial, rather than full, cooperation in the provision of supranational public goods, such as the ESSI.

2.2 | Related Literature

The foundational economic theory on public goods originates from Samuelson (1954), who defines them by their non-rivalrous and non-excludable characteristics, inherently creating free-rider incentives. Lindahl (1919) and Musgrave (1939) further this discussion by addressing optimal cost allocation and highlighting the inherent difficulties associated with voluntary contribution mechanisms. Building upon these insights, Olson (1965) extends the logic to collective action problems, demonstrating how larger groups face amplified challenges due to intensified free-rider incentives—particularly relevant in the context of international defense cooperation.

From a game-theoretic perspective, Olson and Zeckhauser (1966) argue that countries tend to underinvest in shared security due to prevalent free-riding incentives. Yet, empirical studies frequently observe deviations from these predictions, revealing cooperative behaviors within real-world alliances. Hirshleifer (1983) introduces distinct aggregator technologies—summation, best-shot, and weakest-link—to model collective security provision effectively. Sandler (1998) adapts these aggregators specifically to military alliances, noting deterrence aligns best with summation technologies, whereas missile defense resembles a weakest-link structure, necessitating coordinated contributions.

The theoretical concept of burden-sharing is empirically examined by Sandler and Forbes (1980), who find that NATO's defense spending aligns closely with national benefits derived from security contributions. Empirical validation by Sandler (2013), using benefit approximations such as the weighted average of relative population, relative GDP, and relative exposed border length, confirms the correspondence between defense contributions and perceived security benefits. Subsequent refinements by Khanna and Sandler (1996), Sandler and Murdoch (2000), and Bogers et al. (2022) expand this framework, incorporating additional dimensions such as overseas military deployments and peacekeeping efforts.

Recent literature indicates a shift away from traditional burden-sharing dynamics within NATO. Notably, Sandler and Shimizu (2014) and Cooper and Stiles (2021) document declining efficiency in NATO's burden-sharing mechanisms post-2003, empirically rejecting the hypothesis of proportional burden sharing—members do not contribute in proportion to the benefits they receive. These findings raise critical questions regarding the determinants of cooperative behavior in European defense, especially following Russia's annexation of Crimea in 2014 and its subsequent invasion of Ukraine in 2022.

Classical game theory, which predicts free-riding in public goods provision due to individual incentive incompatibility, fails to account for the empirically observed persistence of cooperative behavior in such settings (James Andreoni, 1995; Goeree et al., 2002). Alternative insights from experimental economics demonstrate that individuals often cooperate despite apparent free-riding incentives (Isaac and Walker, 1988; Dreber et al., 2013). Capraro (2013a) proposes a behavioral framework where individuals initially consider cooperative equilibria and subsequently evaluate incentives to defect, consistent with empirical evidence highlighting the importance of reciprocity and the risk of deviation (Fehr and Schurtenberger, 2018; Capraro et al., 2019).

Traditional coalition formation theories (Ray and Vohra, 1997) emphasize incentive compatibility as central to stable alliances. Although historical NATO burden-sharing has demonstrated stability (Sandler and Murdoch, 2000), recent geopolitical shifts and initiatives such as ESSI highlight limitations in traditional models.

This research contributes to the literature by defining the condition for stable coalitions within the behavior model and the burden-sharing literature with the novel ABS for the ESSI. By linking both aspects, we offer an explanatory and predictive framework for the strategic formation of coalitions in Europe. By applying the framework to real-world data from the ESSI, we provide policy-relevant insights for European NATO cooperation and burden sharing.

The remainder of the paper is as follows. Section 2.3 introduces and formally defines the concept of a stable coalition structures within the model of Capraro (2013a), applied to the context of supranational public goods provision and integrates insights from the burden-sharing approach of Sandler and Forbes (1980). Section 2.4 applies the proposed model to the ESSI, analyzing whether the current coalition structure is stable. Section 2.5 concludes and suggests directions for future research.

2.3 | A Model of the Provision of Supranational Public Goods

This section develops the formal definition of stable coalition structure based on the behavioral approach by (Capraro, 2013a) using the standard Linear Public Goods Game. We then briefly discuss the background of the model. Next, we introduce a burden-sharing method for the ESSI, using a novel approximation approach. Finally, building on these foundations, we develop a model that integrates the behavioral approach with the burden-sharing method.

2.3.1 | Formal Description of the Game

Consider a finite set of players, denoted as $P = \{1, 2, \ldots, n\}$ with individual endowment y_i and individual valuation of the public good, denoted by α_i who interact in a game $\mathcal{G}$. A coalition structure p is defined as a partition of the set of players P, meaning it is a collection of pairwise disjoint subsets $S_1, S_2, \ldots, S_k$ such that their union covers P and $\forall S, S' \in p : S \cap S' = \emptyset$. This structure implies that each player belongs to exactly one coalition and no player remains unassigned. The set of all possible coalition structures is denoted by $\mathcal{P}$, which contains every valid partition of P.
Each player $i \in P$ has two pure strategies. The first strategy, denoted as σ^c, represents cooperation, where the player contributes x_i to the coalition, which equals their entire endowment y_i . The second strategy, σ^s, signifies a selfish approach whereby the player withholds contributions entirely and benefits from the public good only if others contribute. The complete strategy profile of all players is expressed as:

$$\sigma = (\sigma_1, \sigma_2, \ldots, \sigma_n), \quad \text{where} \quad \sigma_i \in \{\sigma^s, \sigma^c\}. \tag{2.1}$$

Given the binary nature of strategies in the game, coalition structures take the following form:

$$p = \{C, \{i_1\}, \{i_2\}, \ldots, \{i_k\}\}, \tag{2.2}$$

where the coalition composition is characterized as follows. The set C represents the large coalition, containing either multiple players who commit to collective action or no players. Formally, $C \subseteq P$ with $|C| > 1$ or $C = \emptyset$. The remaining players, $\{i_1\}, \{i_2\}, \ldots, \{i_k\}$, constitute singleton coalitions, who choose not to participate in cooperative efforts yet, may still benefit from the public good generated by the large coalition.

The individual payoff $u_i(\sigma)$ is dependent on coalition structure:

$$u_i(\sigma) = \begin{cases} f_i(C) - x_i(\sigma_i) & \text{if } i \in C \text{ for } C \in p \text{ (player } i \text{ contributes),} \\ f_i(C) & \text{if } i \notin C \text{ (player } i \text{ free-rides),} \end{cases} \tag{2.3}$$

where $f_i(C)$ reflects the benefit from the coalition's provision of the public good. The function $f_i(C)$ is assumed to be strictly increasing in C, indicating that larger coalitions yield higher benefits. In particular, when a player is in a singleton coalition—or if no coalition forms at all—the benefit defaults to zero, i.e.,$f_i(C) = 0$, if $C \in \{\emptyset, \{i\}\}$. This reflects the idea that cooperation generates value only when multiple (at least two) players contribute to the coalition.

Given the uncertainty in coalition formation, each player forms beliefs about their expected payoff $v_i(p)$, which accounts for all possible coalition structures weighted by their probability:[3]

$$v_i(p) = \sum_{p \in \mathcal{P}} \tau_i(p) \cdot u_i(p), \tag{2.4}$$

where $\tau_i(p)$ represents the probability of coalition structure p occurring, with: $\sum_{p \in \mathcal{P}} \tau_i(p) = 1, \forall i \in P$.

2.3.1.1 | Induced Game and Constraints on Allowed Coalitions

The intuition is that individuals anticipate how the game would unfold if they formed coalitions, and act according to their most optimistic forecast. These forecasts are shaped by the individual incentive to deviate from the collective interest (cooperative coalition structure p^c) against the risk of doing so. We formalize this by restricting the set of allowed strategies through a form of tacit binding (Capraro, 2013a).[4]

Definition: The induced game $\text{Ind}(\mathcal{G}, p^c)$ is a modified version of the original game $\mathcal{G}$. The main difference is the set of allowed strategy profiles. In the induced game, only those strategy profiles $\sigma = (\sigma_1, \dots, \sigma_N)$ are allowed where each player's payoff $u_i(\sigma_1, \dots, \sigma_N)$ is at least as large as the expected payoff $v_i(p^c)$, where all players act collectively under the coalition structure p^c that maximizes $v(p)$. Formally expressed as:

$$u_i(\sigma_1, \dots, \sigma_N) \geq v_i(p^c) \quad \forall \ i. \tag{2.5}$$

We use the value $v_i(p^c)$ to define beliefs, implicitly creating a tacit binding among the

---

[3] The calculation method for $\tau_i(p)$ is provided in equation (2.14) and defined as the probability derived from an incentive–risk ratio.

[4] The strategy space is non-empty and compact; however, it is not convex due to the binary choice of strategies. For this reason, the existence of a Nash equilibrium cannot be guaranteed based on Nash (1950).

players.[5] In the following, p^c is defined as the fully cooperative coalition structure.[6] The fully cooperative coalition structure leads to higher expected payoff than $v(p)$, given that the expected payoff $v(p)$ for any other coalition structure p lies between the selfish structure $v(p^s)$ and the fully cooperative structure $v(p^c)$.

2.3.1.2 | Definition of a Stable Coalition Structure

To predict and analyze stable coalition structures, we introduce a set of stability conditions that determine which coalition structures are stable. A stable coalition structure p belongs to a subset $V \subseteq \mathcal{P}$, representing the set of all coalition structures that satisfy these stability conditions:

Condition 1 (Incentive Compatibility): Each player in the large coalition must receive a strictly higher expected payoff in the coalition structure than they would under a selfish structure[7]:

$$v_i(p^c) > v_i(p^s), \quad \forall i \in C. \tag{2.6}$$

Condition 2 (Allowed Coalitions):[8]
No player can deviate from a stable coalition if the resulting coalition structure is not allowed within the defined induced game:

$$\forall j \in P \text{ with } u_j(p^{-j}) > u_j(p) \ \exists i \in P : u_i(p^{-j}) < v_i(p^c) \tag{2.7}$$

where p^{-j} represents a deviation by player j from the current coalition structure—either by leaving the large coalition and becoming a singleton, or by joining the large coalition from a singleton position.
This condition can be reduced in complexity due to the linear public provision function:

$$\exists i \in P : \ u_i(p^{-j}) < v_i(p^c), \text{ where } j \text{ is the player with the smallest contribution } x_j. \tag{2.8}$$

---

[5] Capraro (2013a) uses $u_i(\sigma_1, \ldots, \sigma_N) \geq v_i(\bar{p}) \quad \forall\ i$, where the coalition structure $\bar{p}$ (independent of i maximizes $v(p)$, which is consequently $v(p^c)$.

[6] In the classical Game Theory literature known as the 'Grand Coalition'.

[7] The expected payoff under the selfish coalition structure is $v_i(p^s) = x_i$.

[8] For the sake of theoretical completeness, one could argue that it would be necessary to also examine whether a deviation by the pivotal country i—which is affected by another country's deviation leading to a non-allowed coalition structure—is itself allowed to deviate. In the current case, country j, which is the smallest and thus has minimal impact, deviates in such a way that it moves country i into a coalition structure that is not allowed. From this, it follows that *any* deviation affecting country i is to result in a non-allowed coalition structure. However, this does not mean that a deviation by i has itself been tested to determine whether it would lead *another* player into a non-allowed coalition structure. For simplicity, and because this is a very rare case, due to the linearity of the public provision function and the large impact (by GDP) of the pivotal country, this case is not explicitly stated in the condition but should be kept in mind.

Condition 3 (Existence of a Partial Cooperative Coalition):[9]
This condition is optional and serves to determine the upper bound of the interval for stable partial coalition structures. It is not required for the full cooperative coalition, since it is always part of the induced game.
If a coalition structure $p \neq p^c$ is stable and belongs to the set of allowed strategies, then at least one allowed partial cooperative coalition must exist:

$$u_i(p) \geq v_i(p^c), \quad \forall i \in P. \tag{2.9}$$

2.3.1.3 | Fictitious Example of a Stable Coalition Structure

To illustrate the definition of a stable coalition structure in a simple setting, we analyze a fictitious example in Table 2.1. A more detailed example with real-world data is provided in the Appendix A.1. We begin with the most optimistic scenario, where all players form a fully cooperative coalition: $p^c = \{\{1, 2, 3\}\}$; see the caption of Table 2.1 for the corresponding expected payoffs.

Stage 1 Check allowed coalition structure of the induced game. We have to determine whether this coalition structure is allowed according to the criterion $u_i(p) \geq v_i(p^c)$. Since each player in p^c receives a strictly higher payoff compared to their expected payoff, this condition is satisfied.

Stage 2 (Incentive Compatibility). We check this condition for the coalition structure. In this example, Condition 1 holds for each player: $u_i(p) \geq v_i(p^s), \forall i \in C$.

Stage 3 (Allowed Coalitions). We examine whether players can deviate to a allowed coalition structure from the coalition structure. In this case, Condition 2 is not satisfied, as deviations to the coalition structures $\{\{2, 3\}, \{1\}\}$ and $\{\{1, 2\}, \{3\}\}$ are possible.[10]

Stage 4 (Existence of a Partial Cooperative Coalition). If this condition holds, there must be at least one allowed coalition structure that is not the full cooperative coalition. [11]

All four steps have to be repeated for each coalition structure under consideration to identify stable coalitions. Appendix A.1 illustrates this in detail for other coalition structures using real-world data. Based on the above analysis, the stable coalition structures emerging in equilibrium are:

$$\{\{2, 3\}, \{1\}\} \quad \text{and} \quad \{\{1, 2\}, \{3\}\}.$$

These are the outcomes where no player has an incentive to deviate, and all stability conditions are fulfilled.

---

[9] This condition checks up to which values of α_0 the coalition structure remains part of the allowed strategy profiles—that is, within the induced game defined in Equation (2.5).

[10] The idea behind Condition 2 is that no deviations to alternative coalition structures should be allowed. If such deviations are possible, the condition is not satisfied.

[11] The condition applies to coalition structure $p \neq p^c$, while here we are evaluating p^c itself.

Table 2.1: Fiction Example: Stable coalition structure with three players. Player 1 has an expected payoff of $v_1(p^c) = 1.05$ and contribution $x_1 = 1.00$, player 2 has $v_2(p^c) = 1.25$ and $x_2 = 1.20$, and player 3 has $v_3(p^c) = 0.95$ and $x_3 = 0.90$.

Coalition Structure	Payoff vs. Expected Payoff	Coalition Structure Allowed $u_i(p) \geq v_i(p^c)$	Conditions for SC		
			(1)	(2)	(3)
$\{\{1\}, \{2\}, \{3\}\}$	$u_1 = 1.0 < v_1(p^c)$ $u_2 = 1.2 < v_2(p^c)$ $u_3 = 0.9 < v_3(p^c)$	no		✗	✗
$\{\{1, 2\}, \{3\}\}$	$u_1 = 1.1 > v_1(p^c)$ $u_2 = 1.5 > v_2(p^c)$ $u_3 = 1.5 > v_3(p^c)$	yes	✓	✓	✓
$\{\{1, 3\}, \{2\}\}$	$u_1 = 0.8 < v_1(p^c)$ $u_2 = 1.7 > v_2(p^c)$ $u_3 = 0.6 < v_3(p^c)$	no	✓	✗	✗
$\{\{2, 3\}, \{1\}\}$	$u_1 = 1.3 > v_1(p^c)$ $u_2 = 1.4 > v_2(p^c)$ $u_3 = 1.1 > v_3(p^c)$	yes	✓	✓	✓
$\{\{1, 2, 3\}\}$	$u_1 = 1.2 > v_1(p^c)$ $u_2 = 1.6 > v_2(p^c)$ $u_3 = 1.4 > v_3(p^c)$	yes	✓	✗	

(*Notes.* This table presents the evaluation of coalition structures among three players under a stable coalition framework. Each coalition is assessed based on whether it meets the stability conditions. The column "Payoff vs. Expected Payoff" compares each player's actual payoff $u_i(p)$ with their expected payoff under the fully cooperative coalition structure $v_i(p^c)$. The column "Coalition Structure Allowed" indicates whether the coalition is allowed based on the condition $u_i(p) \geq v_i(p^c)$. The final column verifies if the stability conditions for a Stable Coalition (SC) are satisfied. A checkmark (✓) indicates that the condition is met, while a cross (✗) indicates it is not. The expected payoff $v_i(p^c)$ is calculated as a weighted sum over all possible coalition structures, as defined in equation (2.4), where the weights $\tau_i(p)$ reflect the probability of coalition formation. The contribution x_i represents the full endowment each player commits to the cooperative coalition, as described in equation (2.3), and is relevant for Condition 2.3.1.2 since $v_i(p^s) = x_i$. The results highlight which coalitions form a stable coalition structure, ensuring no player has an incentive to deviate. Condition 2.3.1.2 does not need to be checked for the singleton coalition structure, as it does not represent a cooperative equilibrium. Similarly, Condition 2.3.1.2 does not need to be checked for the fully cooperative coalition, as it does not constitute a partial cooperative coalition.)

2.3.2 | Underlying Framework of the Model

After introducing the induced game and defining the conditions for a stable coalition structure, we review the theoretical foundations underlying our model. Specifically, we discuss insights from Sandler and Forbes (1980), introducing a novel approach to burden-sharing explicitly tailored to the ESSI, as well as the behavioral cooperation framework proposed by Capraro (2013a).

2.3.2.1 | Burden-Sharing

Sandler and Forbes (1980) argue that in the provision of collective defense, aligning allied contributions with received benefits is not merely an aspiration but an emergent expectation in cooperative settings. The study suggests that, over time, the differences between actual defense burdens and those predicted on the basis of benefits should diminish. This convergence is attributed to increased awareness of common interests and an increase in the ratio of excludable benefits to the sum of excludable and non-excludable benefits. With an aggregate measure of allied benefits in hand, it is possible to compare actual defense shares with those derived from the three benefit proxies. There are numerous potential weighting methods for aggregating the various benefit measures (called ABS). Sandler and Forbes (1980) used three equally weighted determinants—a country's share of NATO's total population, its share of NATO's total GDP, and its share of NATO's total exposed border—to determine relative defense burdens and benefits among NATO allies.

Burden Sharing in the ESSI

Building upon the methodology from Sandler and Shimizu (2014), we applied the Wilcoxon signed-rank test approach for the years 1993 to 2022.[12] The null hypothesis—that NATO allies' defense burdens match average derived benefit shares—was consistently rejected at the 0.05 significance level, confirming the earlier findings of Sandler and Shimizu (2014) and further demonstrating that defense expenditures no longer align with derived benefit measures. We used the same weighting as in previous literature to allow for comparability of results. In addition to replicating previous analyses, we implemented a change in the setup of the countries analyzed. Specifically, we used the Wilcoxon signed-rank test approach for European NATO countries.[13] By excluding the United States and Canada from our analysis, we concentrate on the European context where the dynamics of burden-sharing and defense cooperation are distinct from those in the broader NATO alliance. Thus, we tested the alternative hypothesis: "The distributions of defense burdens and average benefit share are the same." An interesting observation we made is that, for all countries within Europe, the different burden-sharing methodologies yields similar results. While the

---

[12] We use the Wilcoxon signed-rank test, a non-parametric method for paired data, to evaluate whether the observed burden shares systematically differ from the derived benefit shares. The test was applied both to single benefit and to the ABS. More details can be found in Chapter 3.3 and Table A.7.

[13] We excluded Iceland from this analysis as well, consistent with prior studies, because it has no military expenditures (Sandler and Forbes, 1980; Khanna and Sandler, 1996, 1997; Sandler and Murdoch, 2000; Sandler and Shimizu, 2014).

alternative hypothesis has been rejected for NATO as a whole since 2003, it is not rejected for NATO countries within Europe, at least from 1993 to 2022. Furthermore, we did not only test for the classic burden-sharing method among European NATO countries but also included the determinant variables "Exposed Border (EB)," "Exposed Border with Russia (EBR)," and "Distance Category (DC)".[14] The alternative hypothesis was not rejected in these cases either. The best alternative determinant for "EB" in the ESSI context, according to the Wilcoxon test, is "EBR." The test is presented in Appendix A.2 (Table A.6) and alternative weightings in Appendix A.4.

$$z_i = \frac{1}{3}\left(\frac{\text{Population}_i}{\sum_j \text{Population}_j} + \frac{\text{GDP}_i}{\sum_j \text{GDP}_j} + \frac{\text{EBR}_i}{\sum_j \text{EBR}_j}\right) \tag{2.10}$$

The empirical results outlined above highlight the complexities of burden-sharing. Next, we incorporate insights from behavioral economics. Specifically, we utilize the model proposed by Capraro (2013a), which accounts for intrinsic motivations and cooperative tendencies among individuals facing social dilemmas.

2.3.2.2 | A Model of Human Cooperation in Social Dilemmas

The model introduced by Capraro (2013a) is based on the intrinsic tendency of individuals, particularly focusing on her inclination toward cooperative behavior. The premise is that a player does not act a priori as a single agent and makes accurate predictions about how the game would play if she were to form coalitions. Then, she acts according to her most optimistic forecast.

Consider a game similar to the one described in Section 2.3.1, with the key distinction that Capraro (2013a) represents a symmetric game with homogeneous endowment as in the model.[15] By applying the *Model of Human Cooperation in Social Dilemmas*, we obtain the following.[16] The function $v_i(p)$ represents the expected payoff of player i when she plays according to the coalition structure p. In fact, this value is defined as an average

$$v_i(p) = \sum_{J \subseteq P \setminus \{i\}} u_{i,J}(p)\tau_{i,J}(p), \tag{2.11}$$

where $\tau_{i,J}(p)$ represents the prior probability that player i assigns to the event 'players in J abandon the coalition structure p' and $u_{i,J}(p)$ is the infimum of payoffs of player i when

---

[14] As an alternative to adjusting the weighting in (2.10) a new method involves considering the direct, indirect, or no border with Russia, called the DC. In this method, countries with a direct border receive 3 points, those with an indirect border receive 2 points, and those with no border receive 1 points. The score for each country is then normalized by dividing it by the sum of all the scores. This assumption is based on the perceived threat from proximity to Russia alone, regardless of the length of the border. More details can be found in Chapter 3.3.

[15] In contrast, the model in Section 4.3 is asymmetric, with heterogeneous endowments.

[16] A more detailed explanation of the "Model of Human Cooperation in Social Dilemmas" can be found in Capraro (2013b).

she plays according to the coalition structure p and players in J abandon the coalition.[17] To build intuition, we present the definitions of incentive and risk in the two-player case in a linear public goods game.[18] The incentive $D_j(p^c)$ of a player j to deviate from the full cooperative coalition structure p^c is defined as the maximal additional payoff it can attain:

$$D_j(p^c) = \sup\Big(u_j(\sigma_i^c, \sigma_j^s) - u_j(\sigma_i^c, \sigma_j^c)\Big). \tag{2.12}$$

The risk R_j of a player j to deviate from the full cooperative coalition structure p^c is defined as the maximal loss they might encounter, if other players also decide to leave the coalition structure. This situation occurs when player i deviates from the coalition structure p^c, either to pursue self-interests or in anticipation of another player's deviation from the coalition structure p^c:

$$R_j(p^c) = \sup\Big(u_j(\sigma_i^c, \sigma_j^c) - u_i(\sigma_i^s, \sigma_j^s)\Big). \tag{2.13}$$

This incentive arises from the possibility of “free-riding” in the absence of exclusivity. The risk $R_j(p^c)$ of deviating from the full cooperative coalition structure σ^c lies in the fact that other players might also follow their self-interested motives, rejecting the full cooperative coalition structure p^c and ultimately resulting in singleton coalitions.

There are several approaches to define the probability $\tau_{i,j}(p^c)$ of player j leaving coalition structure p^c. Among these methods, one involves comparing the incentive and risk associated with deviating from a coalition. This approach is used due to its intuitive and seemingly natural way:

$$\tau_{i,j}(p^c) = \frac{D_j(p^c)}{D_j(p^c) + R_j(p^c)}. \tag{2.14}$$

The probabilities of deviations are independent, i.e. the probability of a group J deviating is the product of the individual players in this group deviating;

$$\tau_{i,J}(p^c) = \prod_{j \in J} \tau_{i,j}(p^c) \cdot \prod_{j \in J^C \setminus \{i\}} (1 - \tau_{i,j}(p^c)), \tag{2.15}$$

where J^C denotes the complement of the set J.

2.3.3 | The Model

The starting point is a simple Linear Public Goods Game. We use the terminology introduced in Section 2.3.1 and Section 2.3.2. The payoff u_i of country i depends on its initial endowment y_i, its contribution x_i, and the collective contributions of all countries scaled

---

[17] We adopt the notation and terminology from Section 2.3.1 to analyze stable coalition structures. In Capraro (2013a), e is used in place of u, respectively, where $\tau_{i,J}(p)$ denotes the probability of deviation by players in J and $e_{i,J}(p)$ the corresponding payoff for player i.

[18] The generalization is presented in Capraro (2013a); however, it is not required for the purposes of this analysis.

by the external threat factor α_0 and the Average Benefit Share z_i:

$$u_i(\sigma_1, \ldots, \sigma_N) = y_i - x_i + z_i \alpha_0 \sum_{j=1}^{N} x_j, \tag{2.16}$$

where y_i is the individual endowment of country i, which is defined as the share of Military Expenditure$_i$ (ME$_i$)[19] in relation to the total ME of the country set [20]

$$y_i = \frac{ME_i}{\sum_{j \in P} ME_j} \quad \in (0, 1). \tag{2.17}$$

x_i is the contribution to the public good, while complete strategy profile of all countries is expressed as $\sigma = (\sigma_1, \ldots, \sigma_n)$, with $\sigma_i \in \{\sigma^s, \sigma^c\}$ represent a binary choice of either contributing nothing (0) or contributing their full endowment y_i. With z_i as defined in equation (2.10), $\alpha_0 \geq 1$ representing an exogenously given threat factor; and $\partial u_i / \partial z_i > 0$, $\partial u_i / \partial \alpha_0 > 0$ and $\partial u_i / \partial x_j > 0$ for all $j \neq i$ (except when contribution is a dominant strategy for i). The latter derivative highlights the influx of strategic interaction between the countries in country i's payoffs. The level of the threat factor α_0 might increase as conflicts escalate. Given the uncertainty in coalition formation, each player forms beliefs about possible coalition structures, weighted by their respective probabilities. The probability $\tau_{i,j}(p^c)$ of player j leaving a full cooperative coalition structure p^c is as in (2.14):

$$\tau_{i,j}(p^c) = \frac{y_j(1 - \alpha_j)}{\alpha_j \sum\limits_{t \in P \setminus \{j\}} y_t}, \tag{2.18}$$

where the incentive $D_j(p^c)$ of a player j to deviate from the coalition structure p^c is $D_j(p^c) = y_j(1 - \alpha_j)$ and the risk $R_j(p^c)$ of a player j to deviate from the coalition structure p^c is $R_j(p^c) = \alpha_j \sum\limits_{t=1}^{N} y_t - y_j$. The probabilities of deviation are assumed to be independent, to simplify the analysis and facilitate tractable calculations of coalition stability. Finally, $v_i(p^c)$ represents the expected payoff of country i when acting according to the coalition structure p^c as in (2.11). This value is composed of the average of $u_{i,J}(p^c)$, the infimum of payoffs when countries in J abandon the coalition, and $\tau_{i,J}(p^c)$ as in (2.15), representing the prior probability of country i assign to the event of countries in J leaving the coalition structure p^c:

---

[19] As the endowment of a country military expenditure (ME) is utilized. However, because the ME is not entirely allocated to joint air defense, the model considers the relative share of each country's ME$_i$ in relation to the total ME. Since z_i is also a fraction less than 1, representing it as a percentage of ME for the endowment makes sense here. If the objection arises that defense spending varies over the years across countries and that GDP might be a better fit, we have already examined this and found very similar results in Appendix A.5.

[20] Actual and potential members of the ESSI.

$$v_i(p^c) = \alpha_i \left(y_i + \sum_{j \in P \setminus \{i\}} (1 - \tau_{i,j}) y_j \right), \quad \text{where} \quad \alpha_i \equiv z_i \alpha_0. \tag{2.19}$$

2.4 | Application to European Sky Shield Initiative

To analyze the strategic stability of the ESSI, we apply the stable coalition conditions derived from our model of supranational public goods provision to real-world data. Our analysis includes 35-countries set, comprising both ESSI participants and neighboring countries that benefit from the initiative without contributing—effectively functioning as free-riders. We classify these free-riders systematically using a spatial criterion: any country located west of the easternmost ESSI participant is treated as a beneficiary and is not a member of the ESSI. A map illustrating this classification is provided in Figure 2.1.

The empirical findings presented in this paper are valid up to the end of December 2024. New developments beyond this point are not included in the main analysis. However, one event from February 2025, where Portugal and Albania join the ESSI, is documented in the Appendix Section A.7, confirming that the conclusions of this chapter remain robust (Bundesministerium der Verteidigung, 2025).

In addition to the ABS calculation method introduced in equation (2.10), we present alternative scenarios in Appendix Sections A.4, A.5 (with relative GDP instead of relative ME as endowment), A.6 (with relative ME as endowment), and A.6.3 (with data for the "DC"). These scenarios incorporate different weighting schemes for determinants such as EB and DC.

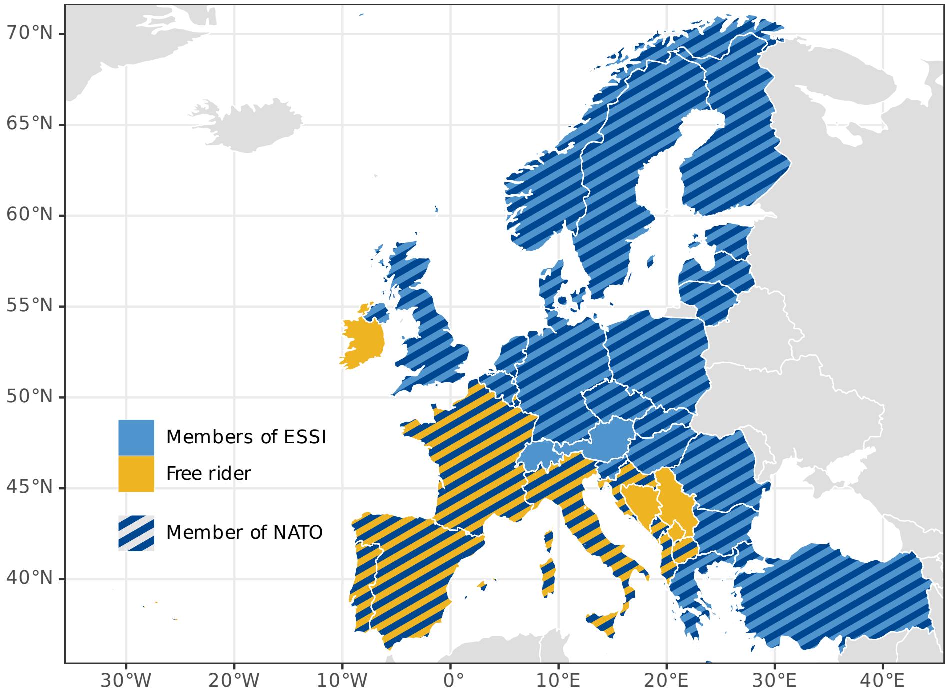


Figure 2.1: Sources: Bundesministerium der Verteidigung (2024); Country classifications as ESSI members, NATO members; and free riders are based on own categorization. Made with Natural Earth.

2.4.1 | A Short History of the ESSI

Due to years of austerity, Germany has made little progress in building a better air defense system. International collaborations such as the development of the Medium Extended Air Defense System (MEADS) and its successor, the Tactical Air Defense System (TLVS), were terminated without procurement agreements. Exorbitant costs are cited as the main reason (Arnold and Arnold, 2023). The trigger for the German initiative was Russia's war of aggression against Ukraine. Russia frequently uses unmanned systems, ballistic missiles, cruise missiles and hypersonic missiles in Ukraine. This demonstrates the importance of a strong air defense to counter future threats. With the ESSI, the European NATO member states want to better protect themselves against attacks by missiles, rockets or aircraft. The goal of the initiative is to strengthen the European pillar of NATO's common air defense. Until October 13, 2022, 15 states ratified the *"European Sky Shield Initiative"* (ESSI). Among them are the 14 NATO member states: Belgium, Bulgaria, Germany, Estonia, Latvia, Lithuania, the Netherlands, Norway, Romania, Slovakia, Slovenia, Czech Republic, Hungary, and the United Kingdom. Additionally, Finland, which was a NATO accession candidate at the time of the ESSI ratification but is currently a NATO member, also signed the agreement North Atlantic Treaty Organization (2022). On February 15, 2023, Denmark, a NATO member state, and Sweden, a NATO accession candidate, signed the membership agreement for the ESSI. On July 11, 2023, Austria and Switzerland, both non-NATO states, joined the ESSI. On February 15, 2024, Greece and Turkey became the newest members of the initiative. Most recently, Prime Minister Tusk announced in April 2024 that Poland will join the ESSI (Reuters, 2024). As of today, a total of 22 states have joined forces to enhance their defenses against attacks from projectiles, missiles, or aerial vehicles. Their objective is to collectively procure, utilize, and maintain the necessary systems for this purpose (Bundesministerium der Verteidigung, 2024).

2.4.2 | No Stable Coalition

The development of the ESSI, as shown in Chapter 2.4.1, demonstrates that neither 15, 17, 19, nor 21 countries have formed a stable coalition. Similarly, in our model, none of the mentioned coalition structures achieve a stable coalition within a 35-country set.[21] Due to that we will show with an example of the model why these coalition structures failed.

Table 2.2: Conditions for stable coalition structure with 15 countries out of a 35-country set

	Values of α_0		
Configuration	Condition 1	Condition 2	Condition 3
z_i^{eb}	$\alpha_0 > 3.356$	$\alpha_0 > 2.185$	$\alpha_0 \leq 2.193$

(*Notes.* The table summarizes the values of α_0 for which each condition is satisfied. The index *"eb"* on z_i refers to the *equal weighting border*, where the Average Benefit Share is calculated as in equation (2.10), using equally weighted determinants: a country's share of total population, share of total GDP, and share of total exposed border with Russia.)

Table 2.2 shows that Condition 1 is only satisfied when $\alpha_0 > 3.356$. This can be interpreted as follows: as α_0 increases, the expected payoff from the full cooperative coalition structure becomes higher than the payoff from the selfish coalition structure. Condition 2, on the other hand, ensures that any deviation from the 15-player coalition leads to a non-allowed coalition structure. Thus, when $\alpha_0 > 2.185$, the coalition structure becomes one from which no player can deviate.[22] Condition 3, by contrast, acts more like a upper limit. As the threat α_0 increases, the expected payoff from the full cooperative coalition structure not only exceeds that of the selfish coalition structure but also surpasses that of the partial

---

[21] In fully cooperative coalitions within 15-, 17-, 19-, 21-, and similarly sized country sets— rather than the broader 35-country set with partial cooperative coalitions—stable coalitions are achieved. However, when the full cooperative coalition coincides with the set of all possible countries, such coalitions emerge only at relatively high values of α_0. In these cases, the coalition fails to capture the spillover effects on neighboring countries outside the set, thereby limiting the broader cooperative impact.

[22] At this point, one might pause and wonder: if the coalition structure is stable and every deviation is non-allowed, why is Condition 1 still necessary? The answer is that even if deviations are non-allowed, it would be contradictory to assume that players would aim for a full cooperative coalition unless the expected payoff from it exceeds that of the selfish coalition structure.

(possible) stable coalition structure. For this reason, α_0 must remain below a certain threshold; otherwise, the expected payoff from the full cooperative coalition becomes too large, turning the partial coalition structure into a non-allowed coalition.
A similar observation is with the 17-, 19-, 21-, and 22-country coalitions within the 35-country set (see in Appendix A.6 Table A.13 for details). Consequently, in the next section, we will explore the possible stable coalition structures.

2.4.3 | Stable Coalition

Under this framework, the current ESSI with 22 members does not constitute a stable coalition structure, as several countries fail to satisfy Condition 1. However, stability can be achieved by extending the coalition to include Italy, France, or both (see Table 2.3). The latter scenario is examined in detail, as it appears feasible both politically and within the model's stability conditions.

Table 2.3: Scenarios for a stable coalition for different configurations with 35 countries

Scenario	α_0
1. The current ESSI with 22 countries	–
2. The current ESSI with 22 countries + Italy	$\alpha_0 \in (4.016, 4.043]$
3. The current ESSI with 22 countries + France	$\alpha_0 \in (4.903, 4.943]$
4. The current ESSI with 22 countries + Italy and + France	$\alpha_0 \in (7.749, 7.849]$

(*Notes.* The table summarizes the possible stable coalitions and the associated values of α_0,presented as an interval. Scenario 1 represents the current ESSI configuration with 22 countries, which is not a stable coalition structure because several countries (Denmark, Netherlands, UK, and Greece) violate Condition 1. Scenarios 2, 3, and 4 explore the possibility of extending the coalition to include Italy, France, or both, which results in stable coalition structure at higher values of α_0. Based on data from the World Bank (2024) and the US Central Intelligence Agency (2024).)

The ESSI framework expanded to include Italy and France is analyzed in Table 2.4, which details the stability conditions as a function of the threat parameter α_0.

Table 2.4: Conditions for stable coalition of the ESSI with Italy and France within 35 countries

	Values of α_0		
Configuration	Condition 1	Condition 2	Condition 3
z_i,	$\alpha_0 > 3.893$	$\alpha_0 > 7.749$	$\alpha_0 \leq 7.849$

(*Notes.* The table summarizes the values of α_0 for which each condition is satisfied.)

Condition 1 is satisfied for $\alpha_0 > 3.893$, ensuring that every country in the coalition C has a higher expected payoff by contributing than by playing the selfish strategy. Conversely, Condition 2 holds when $\alpha_0 > 7.749$. To illustrate this, there are α_0 values where the payoff from deviating for Estonia—the smallest country—exceeds the payoff from remaining in the stable coalition structure (ESSI with Italy and France). In this case, Estonia has an incentive to leave the coalition. To verify whether the stable coalition structure remains stable, we check Condition 2, shifting the focus to other countries when Estonia leaves. Here, UK becomes the pivotal country. According to Condition 2, this strategy profile is not-allowed because after Estonia leaves the coalition, UK's payoff under the resulting coalition structure $u_i(p^{-j})$ is lower than its expected payoff in the full cooperative coalition structure $v_i(p^c)$. While Condition 3 is satisfied for all $\alpha_0 \leq 7.849$, meaning that the payoff from the stable coalition structure is still higher than or equal to the expected payoff of the full cooperative coalition structure. Therefore, all conditions for a stable coalition structure are fulfilled for $\alpha_0 \in (7.749, 7.849]$. This interval represents the range in which the coalition remains stable and no country has an incentive to leave the coalition. For a more detailed analysis, see Appendix Section A.6.1, where Table A.12 presents all data points used in the calculation at $\alpha_0 = 7.75$.

2.4.4 | Data Input for the Stable Coalition: ESSI Framework Expanded to Include Italy and France

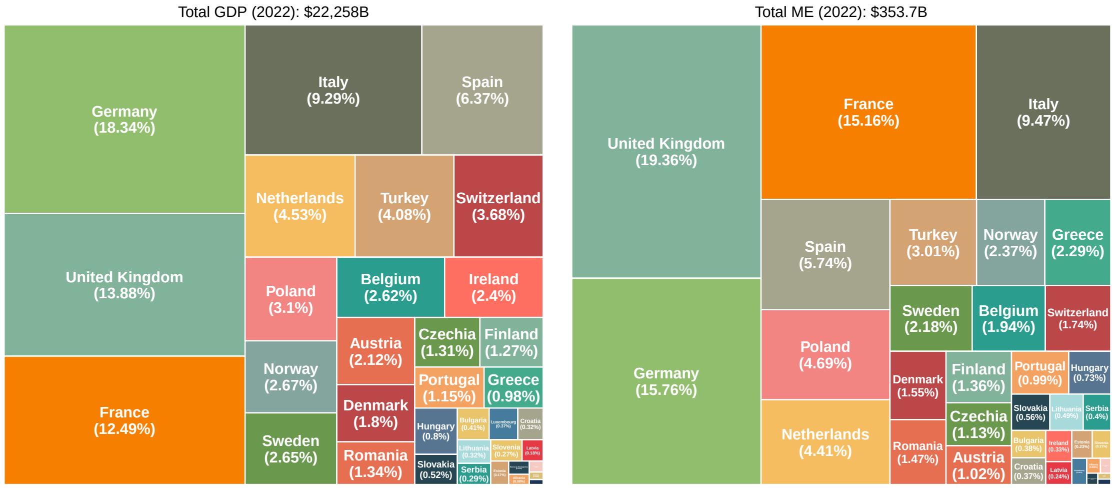
To better illustrate the underlying asymmetries in economic capacity and defense effort, Figure 2.2a and Figure 2.2b present a visual comparison of each country's share of total GDP and ME for 35 countries in 2022, relative to each other. These distributions inform the endowment parameters used in our model, and illustrate why countries such as Germany, France, Italy and the United Kingdom play a central role in burden sharing.

By examining the details in Table 2.5, Finland's high ABS, driven by its extensive EBR, underscores the salience of geographic vulnerability in shaping cooperative behavior.[23] This aligns with the idea that higher perceived risks and benefits from participation amplify the incentive to remain within the coalition. Contrary to initial expectations based on Germany's geographical situation, Germany and the United Kingdom emerge as primary beneficiaries of the ESSI, driven by their large population sizes and GDP values relative to other countries. This substantial economic and demographic weight results in a higher ABS for these nations.

In contrast, smaller states like Estonia and Latvia present a different dynamic. Despite smaller population and GDP shares, their high exposed border values significantly elevate their ABS. This suggests that for smaller countries, geographic risk outweighs other factors, increasing their incentive to cooperate. Interestingly, the absence of exposed borders for several members, including Austria, Belgium, Czechia, and the Netherlands, creates ambiguous incentives in coalitions. These countries rely more on economic and demographic contributions to justify their participation, reflecting a scenario where collective interest is

---

[23] The underlying absolute data used to calculate the ABS is provided in Section A.3, Table A.8



(a) Treemap of each country's share of the total GDP (2022).

(b) Treemap of each country's share of the total ME (2022).

Figure 2.2: The treemaps illustrate the proportional distribution of Gross Domestic Product (GDP) and Military Expenditure (ME) for 35 countries in 2022, relative to each other. Each rectangle represents a country, with the size of the rectangle indicating its relative share of total GDP or ME. The first graph highlights the total GDP distribution across countries ($22,258B), while the second graph focuses on ME distribution ($353.7B). Countries are color-coded consistently across both graphs to facilitate comparison. Data sources include the World Bank (2024).

less driven by immediate external threat factors.

The final row, labeled 'ESSI + Italy + France,' aggregates the values for all participants, providing a reference against normalized totals of population, ME, and exposed border. It is particularly noteworthy that the 24 members of the ESSI framework account for 88% of total GDP within the 35-country set. The model's validity is underscored by the close alignment between the share of ME, at 91.75%, and the total ABS, at 91.78%. A visualization of the ABS is provided in Figure A.5 in the Appendix.

Table 2.5: Key indicators of countries in the European Sky Shield Initiative (ESSI), with 22 members plus Italy and France, in a 35-country set

Country	ESSI Member	ME (%)	ABS Components			ABS (%)
			POP (%)	GDP (%)	EBR (%)	
Albania	FALSE	0.08	0.44	0.08	0.00	0.18
Austria	TRUE	1.02	1.44	2.12	0.00	1.18
Belgium	TRUE	1.94	1.86	2.62	0.00	1.49
Bosnia & Herz.	FALSE	0.05	0.51	0.11	0.00	0.21
Bulgaria	TRUE	0.38	1.03	0.41	0.00	0.48
Croatia	FALSE	0.37	0.61	0.32	0.00	0.31
Czechia	TRUE	1.13	1.70	1.31	0.00	1.00
Denmark	TRUE	1.55	0.94	1.80	0.00	0.91
Estonia	TRUE	0.23	0.21	0.17	12.34	4.24
Finland	TRUE	1.36	0.88	1.27	49.85	17.33
France	TRUE	15.16	10.80	12.49	0.00	7.76
Germany	TRUE	15.76	13.31	18.34	0.00	10.55
Greece	TRUE	2.29	1.66	0.98	0.00	0.88
Hungary	TRUE	0.73	1.53	0.80	0.00	0.78
Ireland	FALSE	0.33	0.81	2.40	0.00	1.07
Italy	TRUE	9.47	9.36	9.29	0.00	6.22
Kosovo	FALSE	0.03	0.28	0.04	0.00	0.11
Latvia	TRUE	0.24	0.30	0.18	12.64	4.37
Lithuania	TRUE	0.49	0.45	0.32	9.94	3.57
Luxembourg	FALSE	0.16	0.10	0.37	0.00	0.16
Montenegro	FALSE	0.03	0.10	0.03	0.00	0.04
Netherlands	TRUE	4.41	2.81	4.53	0.00	2.45
N. Macedonia	FALSE	0.06	0.29	0.06	0.00	0.12
Norway	TRUE	2.37	0.87	2.67	7.27	3.60
Poland	TRUE	4.69	5.85	3.10	7.96	5.64
Portugal	FALSE	0.99	1.65	1.15	0.00	0.93
Romania	TRUE	1.47	3.03	1.34	0.00	1.46
Serbia	FALSE	0.40	1.06	0.29	0.00	0.45
Slovakia	TRUE	0.56	0.86	0.52	0.00	0.46
Slovenia	TRUE	0.21	0.34	0.27	0.00	0.20
Spain	FALSE	5.74	7.59	6.37	0.00	4.65
Sweden	TRUE	2.18	1.67	2.65	0.00	1.44
Switzerland	TRUE	1.74	1.39	3.68	0.00	1.69

Continued on next page

Country	ESSI Member	ME (%)	ABS Components			ABS (%)
			POP (%)	GDP (%)	EBR (%)	
Turkey	TRUE	3.01	13.50	4.08	0.00	5.86
UK	TRUE	19.36	10.77	13.88	0.00	8.22
Total	-	100.00	100.00	100.00	100.00	100.00
ESSI + Italy + France	-	91.75	86.54	88.79	100.00	91.78

(*Notes.* This table presents the participation of countries in the European Sky Shield Initiative (ESSI), with 22 members plus Italy and France, in a 35-country set based on data from World Bank (2024) and US Central Intelligence Agency (2024). For each country, Military Expenditure (ME) as a percentage of total ME across countries is displayed. Additional columns include each country's share of the total population (POP), gross domestic product (GDP) share, and exposed border with Russia (EBR) share. The Average Benefit Share (ABS) represents each country's benefit within the ESSI framework. The final row, "ESSI + Italy + France," provides aggregated values for all ESSI members plus Italy and France, with total column sums normalized to 1 for reference.)

2.4.5 | Analysis of the Stable Coalition: ESSI Framework Expanded to Include Italy and France

At first glance, one might assume that increasing the threat factor α_0 would be sufficient to incentivize broad cooperation within the ESSI. However, as shown in Table 2.6, the marginal benefits remain modest for most countries. Since the individual multiplier α_i is determined by the product $z_i\alpha_0$, it typically stays below 0.8177—even when the threat is high. The only clear exception is Finland, where α_i exceeds 1, creating a dominant strategy to participate in the coalition. A total of 91.75% of ME is generated by 24 countries out of a set of 35 countries. Finland contributes 1.36% with its ME to this total. This total contribution of 91.75 is then multiplied by the multiplier α_i, resulting in a payoff of 1.2325. This can be interpreted as follows: Finland contributes 0.0136 to the total provided ME of 0.9175, and in return, receives valued at 1.2325 of the entire provided amount.

In contrast, the United Kingdom contributes 19.36% to the 91.75% and has a multiplier α_i of 0.6367, meaning that only 63.67% of the entire provided sum benefits the United Kingdom directly. Nevertheless, due to its substantial contribution, the United Kingdom achieves a payoff of 0.5842 of the entire provided amount.

These outcomes reflect a clear pattern: countries with higher multipliers—like Finland, Estonia, and Poland—tend to be geographically on the "front line" to the perceived threat and therefore benefit most from participation. Their willingness to invest in the ESSI stems not from economic might, but from the direct security advantage cooperation provides.

Meanwhile, major contributors such as Germany, the UK, and Turkey also benefit meaningfully, though their relative gains are lower due to less direct exposure. On the other end of the spectrum, countries like Austria, Belgium, and Switzerland, which are geographically more distant and face lower immediate risks, have lower multipliers. With smaller populations and less strategic vulnerability (GDP), their incentives to participate are naturally weaker.

Table 2.6: Determinants of the 24 participants, the computed average benefit share, multiplier α, and payoff for the threat factor $\alpha_0 = 7.75$ in the stable coalition with a country set of 35.

Country	ME (%)	ABS Determinants			ABS (%)	Multiplier α_i	Payoff u_i
		POP (%)	GDP (%)	EBR (%)			
Austria	1.02	1.44	2.12	0.00	1.18	0.0918	0.0842
Belgium	1.94	1.86	2.62	0.00	1.49	0.1157	0.1062
Bulgaria	0.38	1.03	0.41	0.00	0.48	0.0370	0.0340
Czechia	1.13	1.70	1.31	0.00	1.00	0.0775	0.0711
Denmark	1.55	0.94	1.80	0.00	0.91	0.0707	0.0648
Estonia	0.23	0.21	0.17	12.34	4.24	0.3287	0.3016
Finland	1.36	0.88	1.27	49.85	17.33	1.3432	1.2325
France	15.16	10.80	12.49	0.00	7.76	0.6015	0.5519
Germany	15.76	13.31	18.34	0.00	10.55	0.8177	0.7503
Greece	2.29	1.66	0.98	0.00	0.88	0.0680	0.0624
Hungary	0.73	1.53	0.80	0.00	0.78	0.0601	0.0552
Italy	9.47	9.36	9.29	0.00	6.22	0.4818	0.4420
Latvia	0.24	0.30	0.18	12.64	4.37	0.3390	0.3110
Lithuania	0.49	0.45	0.32	9.94	3.57	0.2766	0.2538
Netherlands	4.41	2.81	4.53	0.00	2.45	0.1898	0.1741
Norway	2.37	0.87	2.67	7.27	3.60	0.2792	0.2562
Poland	4.69	5.85	3.10	7.96	5.64	0.4368	0.4007
Romania	1.47	3.03	1.34	0.00	1.46	0.1129	0.1035
Slovakia	0.56	0.86	0.52	0.00	0.46	0.0357	0.0328
Slovenia	0.21	0.34	0.27	0.00	0.20	0.0156	0.0143
Sweden	2.18	1.67	2.65	0.00	1.44	0.1116	0.1024
Switzerland	1.74	1.39	3.68	0.00	1.69	0.1310	0.1202
Turkey	3.01	13.50	4.08	0.00	5.86	0.4540	0.4166
UK	19.36	10.77	13.88	0.00	8.22	0.6367	0.5842
Total	91.75	86.54	88.82	100.00	91.78	7.1126	6.526

(*Notes.* We examine the Stable Coalition. The last column represents the relative payoff of the coalition, indicating the payoff each country receives within the ESSI. The sums of the Multiplier α_i and payoff columns should be understood as cumulative in absolute terms, due to the non-excludability of the provided Supranational Public Good, whereas the other columns sum up to 100% for the 35-country set. Based on data from the World Bank (2024) and the US Central Intelligence Agency (2024).)

To complement the analytical results, we now turn to a visual representation of country-specific outcomes within the ESSI with Figure 2.3. While the previous discussion focused on individual multiplier values and their implications for strategic incentives, the following figure provides a more intuitive understanding of how these dynamics translate into realized payoffs.

Countries positioned at the geopolitical frontier, such as Finland and Poland, exhibit higher relative payoffs due to their elevated security stakes, while economically dominant countries like Germany and the United Kingdom maintain substantial absolute benefits despite their lower multiplier values α_i. This observation is consistent with the model's premise, which asserts that countries with higher stakes in regional security—attributable to geographic proximity or economic leverage—are incentivized to engage actively and invest in ESSI, thereby securing elevated relative payoff values.

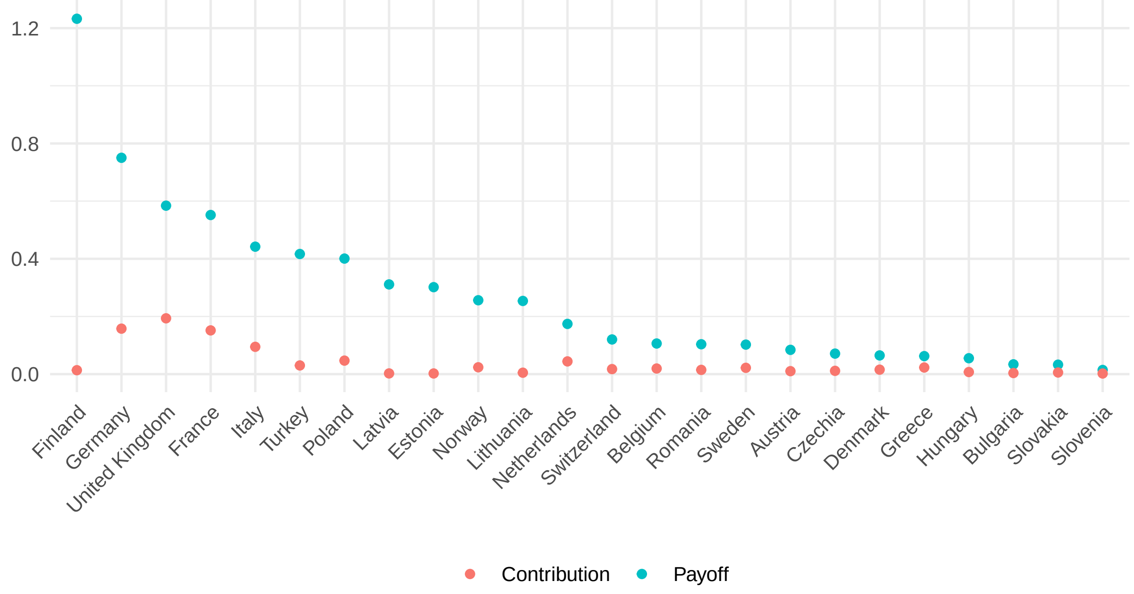


Figure 2.3: The figure plots the 24 participant countries on the horizontal axis, with their contribution and received payoff on the vertical axis given a threat factor $\alpha_0 = 7.75$. Each country's payoff derived from its economic, demographic, and geopolitical factors. Higher payoff values correspond to countries with larger exposed borders with Russia or with greater economic and demographic weights, indicating their higher relative benefits from ESSI participation.

2.5 | Conclusion and Outlook

Concluding Remarks. In this paper, we define the stability conditions for the behavioral model of human cooperation for the provision of public goods, incorporating the idea that players do not act a priori as single agents in the decision-making Capraro (2013a). This allows agents to mentally simulate how coalitions might form if they act collectively and then act according to their most optimistic forecasts. We propose a novel method for computing ABSs, specifically applied to supranational goods such as the ESSI. For the provision of supranational public goods, we are incorporating heterogeneous ABSs and an exogenous threat factor to determine countries' incentives to contribute. We argue that this approach delivers a more nuanced understanding of the provision of supranational public goods and allows us to predict stable coalitions.

While traditional public goods games require a large multiplier to ensure contributing becomes a dominant strategy, this approach allows for contributions without being a dominant strategy. When applied to real-world data from the ESSI, the model explains why certain coalitions fail and identifies the conditions under which stable cooperation can emerge. These findings offer concrete insights for the institutional design of collective action without centralized enforcement.

Critical Reflection. Despite its strengths, the model has several limitations. Free-riding behavior is treated in an idealized manner, assuming no direct spillover effects or reputational consequences for non-contributing countries. In practice, countries that withdraw from coalitions may face diminished diplomatic standing and reduced access to shared security infrastructure. Moreover, the threat parameter α_0 lacks direct measurability. Real-world threat levels are shaped by a complex interplay of intelligence, diplomatic relations, and evolving military provocations. Another important limitation is the exclusion of political factors. For example, the hesitation of France to join the ESSI reflects its leadership role in the PESCO Twister project and concerns about involving non-EU countries in European defense procurement. These political considerations, which have a profound impact on coalition stability and formation, are not addressed in the current framework. Similarly, even though the analysis employs a one-shot game approach, this does not render it unrealistic. Political considerations frequently influence coalition formation in practice; for instance, it has been reported that more countries were initially intended to be invited to join ESSI, yet were excluded due to political issues, such as Turkey's purchase of the Russian S-400 air defense system (Arnold and Arnold, 2023).

Nevertheless, the economic, demographic, and geographic focus provides valuable insights into how cooperative structures emerge and under what conditions they remain stable.

Policy Implication. The model presented in this paper is a simplified representation of complex real-world situations. Its predictions align with the recent developments of the ESSI. The ESSI was initially launched with 15 founding members and has since expanded to include first 17, then 19, then 21, and finally 22 members. According to the model, none of these possible coalitions are stable.[24] For example, for a stable coalition, Italy or France, or both, are needed (depending on the threat level). The model also includes

---

[24] Specifically, no coalition achieves stability at any threat level.

the provision that countries protect European airspace from external threats in accordance with the regulations. What happens in the hypothetical case of a missile attack by the threat country targeting Berlin? The model implicitly assumes that countries along the missile's flight path would take defensive action to uphold collective air defense. In reality, however, it is uncertain whether these countries would intervene—especially if they are not directly targeted and therefore do not perceive an immediate threat. If such a country were to refrain from defensive measures for this reason, it would create a critical security gap along the missile's trajectory. To close this significant security gap, it would be advisable to operate the air defense system independently of the decision-making structures of individual countries. Specifically, a European defense system modeled on Israel's "Iron Dome" would operate autonomously at a supranational level. Implementing such a system could substantially enhance the efficiency and responsiveness of Europe's air defense capabilities. Furthermore, centralized management of air defense operations could eliminate numerous redundancies, optimizing resource allocation and significantly streamlining defense-related processes.

Future Research. The findings open several avenues for further exploration. Future research could refine the models to better capture heterogeneity among member states, accounting for economic disparities and divergent geopolitical interests. Incorporating elements such as individual perceived threat levels, technological innovation, and shifting political landscapes, would improve the model's accuracy and relevance. The key contribution of this model is to identify stable coalitions. It would therefore be valuable to test the robustness of these findings in other settings. One example is the system of border controls against irregular migration to the Schengen Area. The main burden falls on countries with external borders, which bear most of the enforcement costs. Internal borders are generally not controlled. In addition, some Balkan countries, though not part of Schengen, benefit from its control efforts. Notably, while these countries aspire to Schengen membership, they have not yet been integrated. This contrasts with the ESSI, where countries benefit from collective defense efforts without even aspiring to ESSI membership.

APPENDIX | A

The Provision of Supranational Public Goods

Appendix

The appendix is structured as follows. Section A.1 presents a step-by-step illustration of how the stable coalition is determined, using an example with three selected neighboring countries and four different threat scenarios. Section A.2 follows with a statistical analysis using the Wilcoxon signed-rank test to assess the concordance between defense burdens and average benefit shares. Section A.3 lists the input variables—ME and GDP—for the 35-country set with 22 ESSI member plus Italy and France. Section A.4 examines the robustness of the model. Section A.5 replicates the main analysis from Section B.6, but uses GDP instead of ME as the endowment input. Section A.6 provides a more detailed presentation of the main analysis, showcasing different cases and additional results. In Section A.6.3, the geographical threat factor is re-specified using the DC instead of the EBR. Finally, Section A.7 provides a brief analysis with the most recent ESSI members, Albania and Portugal. This section also applies the model first with ME as the endowment, then with GDP, and finally replacing EBR with the DC.

A.1 | Illustrative Example for a Stable Coalition for Selected Threat Factors with Belgium, Germany and the Netherlands

This example examines three neighboring countries that aim to jointly provide air defense. While the scenario is stylized, the underlying data is real. The illustration serves to build intuition for how a stable coalition is identified. The three countries in this example are Belgium, Germany, and the Netherlands. Therefore, the player set is given by $P = \{Belgium, Germany, Netherlands\}$. In the following, subscript 1 refers to Belgium, 2 to Germany and 3 to the Netherlands. p^c denotes the fully cooperative coalition structure and the p^s selfish coalition structure. p^{-j} refers to the coalition structure, where country j deviates from coalition structure p, but the other countries still play according to it. Notably, the coalition structure p^s is the only Nash equilibrium of the original game, where countries do not anticipate how the game would unfold if they formed coalitions, and act according to their most optimistic forecast. In contrast, the induced game incorporates strategic forecasting and a stable coalition can emerge only if the conditions outlined in Section 2.3.1.2 are satisfied.

Table A.1: Absolute and relative values of indicators for countries in the coalition with Belgium, Germany, and the Netherlands.

Absolute Values

Country	**ME (B USD)**	**ABS Components**		
		POP (millions)	**GDP (B USD)**	**EBR (km)**
Belgium	6.87	11.69	583.61	0
Germany	55.76	83.80	4082.47	0
Netherlands	15.61	17.70	1009.40	0
Total	78.24	113.19	5675.48	0

Relative Values

	ME (%)				**ABS (%)**
		POP (%)	**GDP (%)**	**EBR (%)**	
Belgium	8.78	10.32	10.28	0	10.30
Germany	71.27	74.04	71.93	0	72.98
Netherlands	19.95	15.64	17.79	0	16.71
Total	100.00	100.00	100.00	0	99.99

(*Notes.* This table presents the participation of countries in the coalition, with 3 members, in a 3-country set, based on data from World Bank (2024) and US Central Intelligence Agency (2024). For each country, Military Expenditure (ME), population (POP), gross domestic product (GDP), and exposed border with Russia (EBR) are presented in both absolute values and relative percentages. The Average Benefit Share (ABS) represents each country's benefit within the coalition framework. The final row provides aggregated values, with total column sums normalized to 1 for reference.)

The possible coalition structures:

$$\{\{1\},\{2\},\{3\}\}, \quad \{\{1,2\},\{3\}\}, \quad \{\{1,3\},\{2\}\}, \quad \{\{2,3\},\{1\}\}, \quad \{\{1,2,3\}\}$$

We focus on all coalition structures as described in Section 2.3.1[1].

A.1.1 | Case: $\alpha_0 = 1$

In this example, $\alpha_0 = 1$, and it is assumed that no threat exists.
Belgium:

$$\begin{aligned} y_1 &= 0.0878 \\ z_1 &= 0.1030 \end{aligned}$$

$$\begin{aligned} D_1(p^c) &= u(p^{c-1}) - u(p^c) = 0.0787 \\ R_1(p^c) &= u(p^c) - u(p^s) = 0.0153 \end{aligned}$$

$$\begin{aligned} \tau_{i,1}(p^c) &= \begin{cases} \frac{D_1(p^c)}{D_1(p^c)+R_1(p^c)} & \text{if} \quad D_1(p^c) > 0, R_1(p^c) > 0 \\ 1 & \text{if} \quad D_1(p^c) > 0, R_1(p^c) < 0 \\ 0 & \text{if} \quad D_1(p^c) < 0 \end{cases} \\ &= 0.8376 \end{aligned}$$

---

[1] We exclude the ones where only one country is contributing to the public good. It does not seem reasonable for a country to contribute to its own air defense while sharing the payoff with others. Therefore, in the case where only one country contributes while others free-ride, the payoff is treated as if the country did not contribute to the joint air defense but instead to its own air defense, which remains exclusively its own.

$$v_1(p^c) = \alpha_0 z_1 \Big[\tau_{1,\{2,3\}}(p) \quad (y_1) \quad + \tau_{1,\{3\}}(p) \quad (y_1 + y_2)$$

$$+ \tau_{1,\{2\}}(p) \quad (y_1 + y_3) \quad + \tau_{1,\emptyset} \quad (y_1 + y_2 + y_3)(p) \Big]$$

$$= \alpha_0 z_1 \Big[\tau_{1,2}(p)\tau_{1,3}(p) \quad (y_1) \quad + (1 - \tau_{1,2}(p))\tau_{1,3}(p) \quad (y_1 + y_2)$$

$$+ \tau_{1,2}(p)(1 - \tau_{1,3}(p))(y_1 + y_3) \quad + (1 - \tau_{1,2}(p))(1 - \tau_{1,3}(p))(y_1 + y_2 + y_3) \Big]$$

$$v_1(p^c) = \underbrace{0.1031}_{1 \cdot 0.1031} \Big[\underbrace{0.9184}_{0.9184 \cdot 1} \quad (0.0878) \quad + \underbrace{0.0816}_{(1-0.9184)\cdot 1} \quad (0.0878 + 0.7127)$$

$$+ \underbrace{0}_{0.9184 \cdot (1-1)} \quad (0.0878 + 0.1995) + \underbrace{0}_{(1-0.9184)\cdot(1-1)} \quad (0.0878 + 0.7127 + 0.1995) \Big]$$

$$v_1(p^c) = 0.0150$$

Germany:

$y_2 = 0.7127$ $D_2 = 0.1926$ $\tau_{i,2}(p^c) = 0.9184$

$z_2 = 0.7298$ $R_2 = 0.0171$ $v_2(p^c) = 0.5356$

Netherlands:

$y_2 = 0.1995$ $D_2 = 0.1661$ $\tau_{i,2}(p^c) = 1$

$z_2 = 0.1671$ $R_2 = -0.0324$ $v_2(p^c) = 0.0454$

The captions for the following tables—A.2, A.3, A.4, and A.5—are presented here. (*Notes.* This table presents the evaluation of coalition structures among three players. Each coalition is assessed based on whether it meets the stability conditions. The column "Payoff vs. Expected Payoff" compares each player's actual payoff $u_i(p)$ with their expected payoff under the fully cooperative coalition structure $v_i(p^c)$. The column "Coalition Structure Allowed" indicates whether the coalition is allowed based on the condition $u_i(p) \geq v_i(p^c)$. The final column verifies if the stability conditions for a Stable Coalition (SC) are satisfied. A checkmark (✓) indicates that the condition is met, while a cross (✗) indicates it is not. The expected payoff $v_i(p^c)$ is calculated as a weighted sum over all possible coalition structures, as defined in equation (2.4), where the weights $\tau_i(p)$ reflect the probability of coalition formation. The contribution x_i represents the full endowment each player commits to the cooperative coalition, as described in equation (2.3). Condition 1 does not need to be checked for the singleton coalition structure, as it does not represent a cooperative equilibrium. Similarly, Condition 3 does not need to be checked for the fully cooperative coalition, as it does not constitute a partial cooperative coalition.)

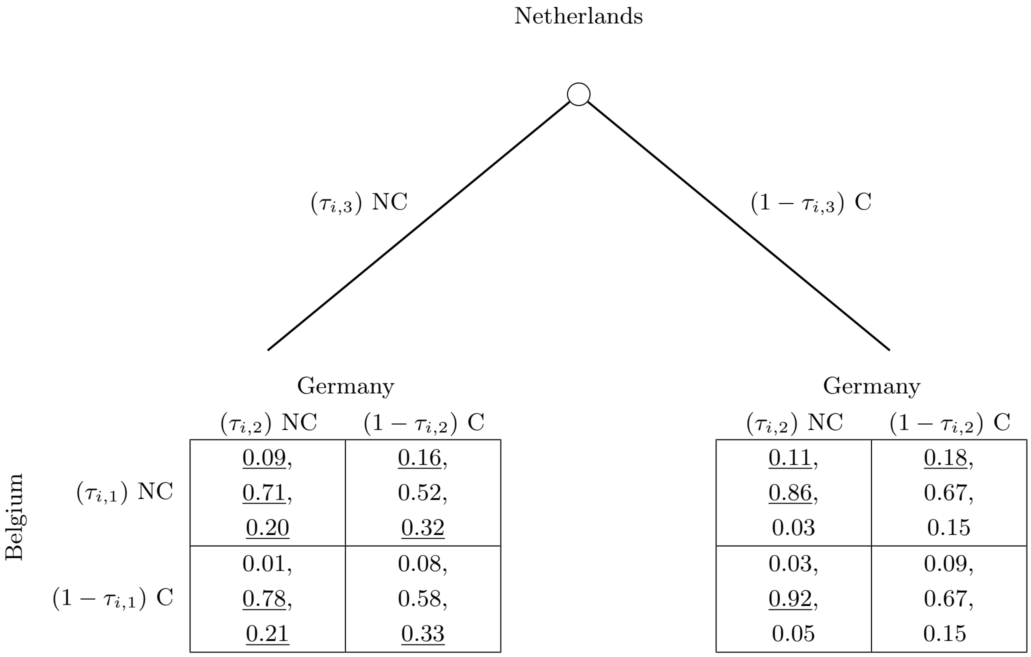
Table A.2: Conditions for a stable coalition ($\alpha_0 = 1.000$). Player 1 has an expected payoff of $v_1(p^c) = 0.0150$ and contribution $x_1 = 0.0878$, Player 2 has $v_2(p^c) = 0.5356$ and $x_2 = 0.7127$, and Player 3 has $v_3(p^c) = 0.0454$ and $x_3 = 0.1995$.

Coalition Structure	Payoff vs. Expected Payoff	Coalition Structure Allowed	Conditions for SC		
		$u_i(p) \geq v_i(p^c)$	(1)	(2)	(3)
{{1}, {2}, {3}}	$u_1 = y_1 = 0.0878 > v_1(p^c)$ $u_2 = y_2 = 0.7127 > v_2(p^c)$ $u_3 = y_3 = 0.1995 > v_3(p^c)$	yes		✓	✓
{{1, 2}, {3}}	$u_1 = \alpha_0 z_1(y_1 + y_2) = 0.0825 > v_1(p^c)$ $u_2 = \alpha_0 z_2(y_1 + y_2) = 0.5842 > v_2(p^c)$ $u_3 = y_3 + \alpha_0 z_2(y_1 + y_2) = 0.3333 > v_3(p^c)$	yes	✗	✗	✓
{{1, 3}, {2}}	$u_1 = \alpha_0 z_1(y_1 + y_3) = 0.0296 > v_1(p^c)$ $u_2 = y_2 + \alpha_0 z_2(y_1 + y_3) = 0.9224 > v_2(p^c)$ $u_3 = \alpha_0 z_2(y_1 + y_3) = 0.0480 > v_3(p^c)$	yes	✗	✗	✓
{{2, 3}, {1}}	$u_1 = y_1 + \alpha_0 z_1(y_2 + y_3) = 0.1818 > v_1(p^c)$ $u_2 = \alpha_0 z_2(y_2 + y_3) = 0.6658 > v_2(p^c)$ $u_3 = \alpha_0 z_2(y_2 + y_3) = 0.1525 > v_3(p^c)$	yes	✗	✗	✓
{{1, 2, 3}}	$u_1 = \alpha_0 z_1(y_1 + y_2 + y_3) = 0.1030 > v_1(p^c)$ $u_2 = \alpha_0 z_2(y_1 + y_2 + y_3) = 0.7298 > v_2(p^c)$ $u_3 = \alpha_0 z_2(y_1 + y_2 + y_3) = 0.1671 > v_3(p^c)$	yes	✗	✗	

⇒ Condition 1 $v_i(p^c) \geq y_i$ is not satisfied by all countries. It is not reasonable to assume that the countries will form a coalition.

Since all coalition structures are allowed, and all countries have a positive incentive to abandon the coalition in every coalition structure, the only stable coalition equilibrium is the non-cooperative coalition structure.

Normal Form



	$(\tau_{i,2})$ NC	$(1-\tau_{i,2})$ C
$(\tau_{i,1})$ NC	$\underline{0.09}$, $\underline{0.71}$, $\underline{0.20}$	$\underline{0.16}$, 0.52, $\underline{0.32}$
$(1-\tau_{i,1})$ C	0.01, $\underline{0.78}$, $\underline{0.21}$	0.08, 0.58, $\underline{0.33}$

	$(\tau_{i,2})$ NC	$(1-\tau_{i,2})$ C
$(\tau_{i,1})$ NC	$\underline{0.11}$, $\underline{0.86}$, 0.03	$\underline{0.18}$, 0.67, 0.15
$(1-\tau_{i,1})$ C	0.03, $\underline{0.92}$, 0.05	0.09, 0.67, 0.15

Figure A.1: The normal-form representation depicts a simultaneous game involving three countries: Belgium, Germany, and the Netherlands. Each country can choose between contributing (C) or not contributing (NC) to the coalition. The dominant actions are underlined. Black numbers indicate coalition structures that belong to the set of allowed strategies.

A.1.2 | Case: $\alpha_0 = 1.282$

Belgium

$y_1 = 0.0878$ $D_1 = 0.0762$ $\tau_{i,1}(p^c) = 0.6322$

$z_1 = 0.1030$ $R_1 = 0.0443$ $v_1(p^c) = 0.0919$

Germany:

$y_2 = 0.7127$ $D_2 = 0.0459$ $\tau_{i,2}(p^c) = 0.1706$

$z_2 = 0.7298$ $R_2 = 0.2229$ $v_2(p^c) = 0.7131$

Netherlands:

$y_3 = 0.1995$ $D_3 = 0.1567$ $\tau_{i,3}(p^c) = 0.9139$

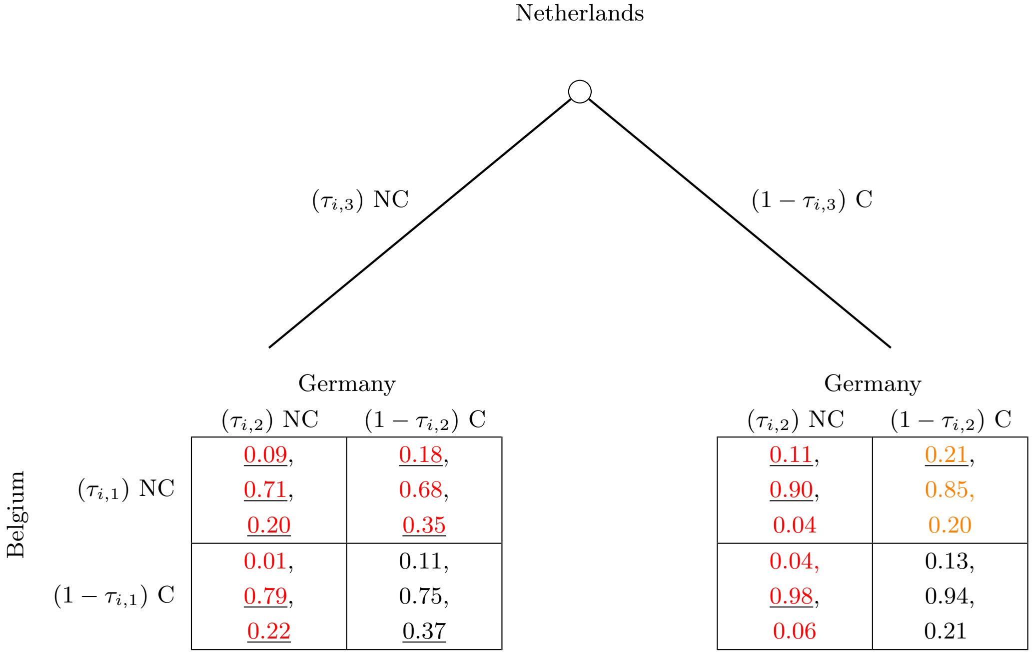
$z_3 = 0.1671$ $R_3 = 0.0148$ $v_3(p^c) = 0.1763$

Table A.3: Player 1 has an expected payoff of $v_1(p^c) = 0.0919$ and contribution $x_1 = 0.0878$, Player 2 has $v_2(p^c) = 0.7131$ and $x_2 = 0.7127$, and Player 3 has $v_3(p^c) = 0.1763$ and $x_3 = 0.1995$.

Coalition Structure	Payoff vs. Expected Payoff	Coalition Structure Allowed	Conditions for SC		
		$u_i(p) \geq v_i(p^c)$	(1)	(2)	(3)
{{1}, {2}, {3}}	$u_1 = 0.0878 < v_1(p^c)$ $u_2 = 0.7127 < v_2(p^c)$ $u_3 = 0.1995 > v_3(p^c)$	no		✓	✗
{{1, 2}, {3}}	$u_1 = 0.1057 > v_1(p^c)$ $u_2 = 0.7490 > v_2(p^c)$ $u_3 = 0.3710 > v_3(p^c)$	yes	✓	✓	✓
{{1, 3}, {2}}	$u_1 = 0.0379 < v_1(p^c)$ $u_2 = 0.9815 > v_2(p^c)$ $u_3 = 0.0615 < v_3(p^c)$	no	✗	✓	✗
{{2, 3}, {1}}	$u_1 = 0.2082 > v_1(p^c)$ $u_2 = 0.8535 > v_2(p^c)$ $u_3 = 0.1954 > v_3(p^c)$	yes	✗	✓	✓
{{1, 2, 3}}	$u_1 = 0.1321 > v_1(p^c)$ $u_2 = 0.9357 > v_2(p^c)$ $u_3 = 0.2142 > v_3(p^c)$	yes	✗	✗	

⇒ Condition 1, $v_i(p^c) \geq y_i$, is not satisfied for Player 3 (Netherlands). Given this, it is unreasonable to expect Player 3 to join any coalition.
⇒ As a result, the coalition structure {{Belgium, Germany}, {Netherlands}} emerges as the unique stable coalition structure in this game.

Normal Form



Belgium	Germany ($\tau_{i,2}$) NC	Germany ($1-\tau_{i,2}$) C
($\tau_{i,1}$) NC	0.09, 0.71, 0.20	0.18, 0.68, 0.35
($1-\tau_{i,1}$) C	0.01, 0.79, 0.22	0.11, 0.75, 0.37

Belgium	Germany ($\tau_{i,2}$) NC	Germany ($1-\tau_{i,2}$) C
($\tau_{i,1}$) NC	0.11, 0.90, 0.04	0.21, 0.85, 0.20
($1-\tau_{i,1}$) C	0.04, 0.98, 0.06	0.13, 0.94, 0.21

Figure A.2: The normal-form representation depicts a simultaneous game involving three countries: Belgium, Germany, and the Netherlands. Each country can choose between contributing (C) or not contributing (NC) to the coalition. The dominant actions are underlined. Black numbers indicate coalition structures that belong to the set of allowed strategies, while red numbers represent those that do not. The orange number corresponds to a coalition structure where Condition 1 is not satisfied, preventing it from being stable despite being part of the allowed strategy set.

A.1.3 | Case: $\alpha_0 = 1.332$

Belgium

$y_1 = 0.0878$ $D_1 = 0.0757$ $\tau_{i,1}(p^c) = 0.6049$
$z_1 = 0.1030$ $R_1 = 0.0495$ $v_1(p^c) = 0.1065$

Germany:

$y_2 = 0.7127$ $D_2 = 0.0199$ $\tau_{i,2}(p^c) = 0.0711$
$z_2 = 0.7298$ $R_2 = 0.2594$ $v_2(p^c) = 0.7518$

Netherlands:

$y_3 = 0.1995$ $D_3 = 0.1551$ $\tau_{i,3}(p^c) = 0.8703$
$z_3 = 0.1671$ $R_3 = 0.2594$ $v_3(p^c) = 0.1995$

Table A.4: Player 1 has an expected payoff of $v_1(p^c) = 0.1065$ and contribution$x_1 = 0.0878$, Player 2 has $v_2(p^c) = 0.7518$ and $x_2 = 0.7127$, and Player 3 has $v_3(p^c) = 0.1995$ and $x_3 = 0.1995$.

Coalition Structure	Payoff vs. Expected Payoff	Coalition structure allowed	Conditions for SC		
		$u_i(p) \geq v_i(p^c)$	(1)	(2)	(3)
{{1}, {2}, {3}}	$u_1 = 0.0878 < v_1(p^c)$ $u_2 = 0.7127 < v_2(p^c)$ $u_3 = 0.1995 = v_3(p^c)$	no		✓	✓
{{1, 2}, {3}}	$u_1 = 0.1099 > v_1(p^c)$ $u_2 = 0.7782 > v_2(p^c)$ $u_3 = 0.3777 > v_3(p^c)$	yes	✓	✓	✓
{{1, 3}, {2}}	$u_1 = 0.0394 < v_1(p^c)$ $u_2 = 0.9920 > v_2(p^c)$ $u_3 = 0.0639 < v_3(p^c)$	no	✓	✓	✗
{{2, 3}, {1}}	$u_1 = 0.2130 > v_1(p^c)$ $u_2 = 0.8868 > v_2(p^c)$ $u_3 = 0.2031 > v_3(p^c)$	yes	✓	✓	✓
{{1, 2, 3}}	$u_1 = 0.1372 > v_1(p^c)$ $u_2 = 0.9721 > v_2(p^c)$ $u_3 = 0.2226 > v_3(p^c)$	yes	✓	✗	

⇒ The coalition structures {{Belgium, Germany}, {Netherlands}} and {{Germany, Netherlands}, {Belgium}} emerges as the stable coalition structure in this game.

Normal Form

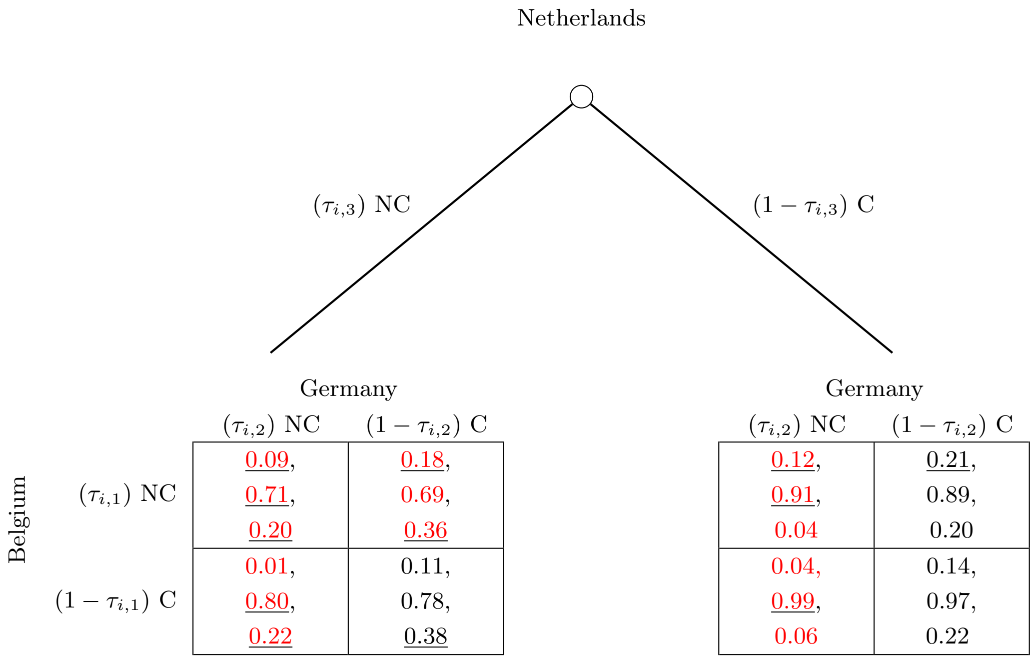


Figure A.3: The normal-form representation depicts a simultaneous game involving three countries: Belgium, Germany, and the Netherlands. Each country can choose between contributing (C) or not contributing (NC) to the coalition. The dominant actions are underlined. Black numbers indicate coalition structures that belong to the set of allowed strategies, while red numbers represent those that do not.

A.1.4 | Case: $\alpha_0 = 1.349$

Belgium

$y_1 = 0.0878$ $D_1 = 0.0756$ $\tau_{i,1}(p^c) = 0.596$

$z_1 = 0.1030$ $R_1 = 0.0512$ $v_1(p^c) = 0.1114$

Germany:

$y_2 = 0.7127$ $D_2 = 0.0110$ $\tau_{i,2}(p^c) = 0.0389$

$z_2 = 0.7298$ $R_2 = 0.2718$ $v_2(p^c) = 0.7649$

Netherlands:

$y_3 = 0.1995$ $D_3 = 0.1545$ $\tau_{i,3}(p^c) = 0.8562$

$z_3 = 0.1671$ $R_3 = 0.0260$ $v_3(p^c) = 0.2074$

Table A.5: Player 1 has an expected payoff of $v_1(p^c) = 0.1114$ and contribution $x_1 = 0.0878$, Player 2 has $v_2(p^c) = 0.7649$ and $x_2 = 0.7127$, and Player 3 has $v_3(p^c) = 0.2074$ and $x_3 = 0.1995$.

Coalition Structure	Payoff vs. Expected Payoff	Coalition Structure Allowed	Conditions for SC		
		$u_i(p) \geq v_i(p^c)$	(1)	(2)	(3)
{{1}, {2}, {3}}	$u_1 = 0.0878 < v_1(p^c)$ $u_2 = 0.7127 < v_2(p^c)$ $u_3 = 0.1995 < v_3(p^c)$	no	✓	✗	✗
{{1, 2}, {3}}	$u_1 = 0.1113 < v_1(p^c)$ $u_2 = 0.7881 < v_2(p^c)$ $u_3 = 0.3800 > v_3(p^c)$	no	✓	✗	✗
{{1, 3}, {2}}	$u_1 = 0.0399 < v_1(p^c)$ $u_2 = 0.9957 > v_2(p^c)$ $u_3 = 0.0648 < v_3(p^c)$	no	✓	✗	✗
{{2, 3}, {1}}	$u_1 = 0.2146 > v_1(p^c)$ $u_2 = 0.8981 > v_2(p^c)$ $u_3 = 0.2057 < v_3(p^c)$	no	✓	✗	✗
{{1, 2, 3}}	$u_1 = 0.1390 > v_1(p^c)$ $u_2 = 0.9846 > v_2(p^c)$ $u_3 = 0.2254 > v_3(p^c)$	yes	✓	✓	

Normal Form

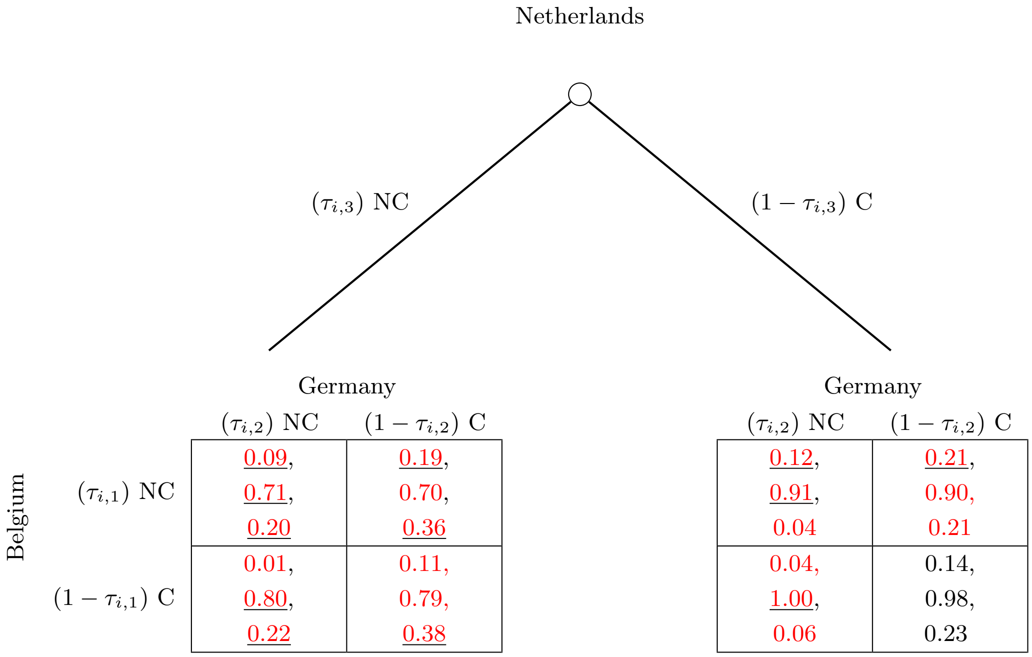


Figure A.4: The normal-form representation depicts a simultaneous game involving three countries: Belgium, Germany, and the Netherlands. Each country can choose between contributing (C) or not contributing (NC) to the coalition. The dominant actions are underlined. Black numbers indicate coalition structures that belong to the set of allowed strategies, while red numbers represent those that do not.

⇒ The coalition structure {{Belgium, Germany, Netherlands}} emerges as the stable coalition structure in this game.

A.2 | Wilcoxon Signed-Rank Test

Table A.6: Wilcoxon signed-rank correlation of ME/European NATO ME and alternative Average Benefit Shares

		ABS Exposed Border	ABS Exposed Border with Russia	ABS Distance Category
Year	Size	R (p)	R (p)	R (p)
1993	13	39 (0.68)	23 (0.13)	29 (0.27)
1994	13	40 (0.74)	25 (0.17)	28 (0.24)
1995	13	39 (0.68)	25 (0.17)	31 (0.34)
1996	13	40 (0.74)	24 (0.15)	30 (0.31)
1997	13	41 (0.79)	22 (0.11)	29 (0.27)
1998	13	39 (0.68)	22 (0.11)	29 (0.27)
1999	16	55 (0.53)	44 (0.23)	48 (0.32)
2000	16	55 (0.53)	42 (0.19)	47 (0.30)
2001	16	56 (0.56)	49 (0.35)	47 (0.30)
2002	16	54 (0.50)	47 (0.30)	44 (0.23)
2003	16	56 (0.56)	48 (0.32)	44 (0.23)
2004	23	92 (0.17)	134 (0.92)	80* (0.08)
2005	23	80* (0.08)	137 (0.99)	74* (0.05)
2006	23	86 (0.12)	136 (0.96)	78* (0.07)
2007	23	88 (0.13)	135 (0.94)	74* (0.05)
2008	23	96 (0.21)	137 (0.99)	86 (0.12)
2009	25	103 (0.11)	160 (0.96)	100* (0.10)
2010	25	103 (0.11)	160 (0.96)	95* (0.07)
2011	25	102 (0.11)	158 (0.92)	94* (0.07)
2012	25	102 (0.11)	158 (0.92)	90* (0.05)
2013	25	102 (0.11)	162 (1.00)	94* (0.07)
2014	25	90* (0.05)	153 (0.81)	88** (0.05)
2015	25	95* (0.07)	156 (0.87)	84** (0.03)
2016	25	95* (0.07)	159 (0.94)	92* (0.06)
2017	26	108* (0.09)	174 (0.98)	101* (0.06)
2018	26	116 (0.14)	172 (0.94)	101* (0.06)
2019	26	108* (0.09)	149 (0.52)	97** (0.05)
2020	27	133 (0.19)	175 (0.75)	108* (0.05)
2021	27	139 (0.24)	173 (0.71)	116* (0.08)
2022	27	147 (0.32)	162 (0.53)	119* (0.10)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. In parentheses are prob-values, indicating the probability of a type I error. ***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

Table A.7: Wilcoxon signed-rank correlation of ME/European NATO ME and single benefit shares

		GDP	POP	EB	EBR	DC
Year	Size	R (p)	R (p)	R (p)	R (p)	R (p)
1993	13	39 (0.68)	43 (0.89)	40 (0.74)	13** (0.02)	42 (0.84)
1994	13	40 (0.74)	44 (0.95)	40 (0.74)	13** (0.02)	42 (0.84)
1995	13	43 (0.89)	43 (0.89)	41 (0.79)	13** (0.02)	41 (0.79)
1996	13	42 (0.84)	45 (1.00)	40 (0.74)	13** (0.02)	42 (0.84)
1997	13	41 (0.79)	40 (0.74)	40 (0.74)	13** (0.02)	43 (0.89)
1998	13	43 (0.89)	42 (0.84)	40 (0.74)	13** (0.02)	42 (0.84)
1999	16	56 (0.56)	62 (0.78)	63 (0.82)	31* (0.06)	60 (0.71)
2000	16	54 (0.50)	57 (0.60)	60 (0.71)	31* (0.06)	59 (0.67)
2001	16	56 (0.56)	58 (0.63)	58 (0.63)	31* (0.06)	58 (0.63)
2002	16	59 (0.67)	57 (0.60)	60 (0.71)	31* (0.06)	57 (0.60)
2003	16	58 (0.63)	58 (0.63)	61 (0.74)	31* (0.06)	59 (0.67)
2004	23	107 (0.36)	103 (0.30)	128 (0.78)	96 (0.21)	102 (0.29)
2005	23	111 (0.43)	104 (0.31)	138 (1.00)	97 (0.22)	105 (0.33)
2006	23	102 (0.29)	99 (0.25)	134 (0.92)	96 (0.21)	106 (0.34)
2007	23	98 (0.23)	96 (0.21)	135 (0.94)	96 (0.21)	107 (0.36)
2008	23	95 (0.20)	108 (0.38)	136 (0.96)	98 (0.23)	109 (0.39)
2009	25	98* (0.09)	127 (0.35)	149 (0.73)	108 (0.15)	121 (0.28)
2010	25	98* (0.09)	122 (0.29)	159 (0.94)	108 (0.15)	121 (0.28)
2011	25	104 (0.12)	126 (0.34)	157 (0.89)	108 (0.15)	118 (0.24)
2012	25	105 (0.13)	112 (0.18)	155 (0.85)	108 (0.15)	119 (0.25)
2013	25	108 (0.15)	111 (0.17)	156 (0.87)	108 (0.15)	115 (0.21)
2014	25	107 (0.14)	108 (0.15)	152 (0.79)	108 (0.15)	115 (0.21)
2015	25	111 (0.17)	103 (0.11)	153 (0.81)	108 (0.15)	113 (0.19)
2016	25	126 (0.34)	112 (0.18)	157 (0.89)	108 (0.15)	119 (0.25)
2017	26	149 (0.52)	119 (0.16)	166 (0.82)	113 (0.12)	127 (0.23)
2018	26	150 (0.53)	127 (0.23)	172 (0.94)	113 (0.12)	128 (0.24)
2019	26	170 (0.90)	126 (0.22)	169 (0.88)	113 (0.12)	130 (0.26)
2020	27	186 (0.95)	147 (0.32)	186 (0.95)	119* (0.10)	128 (0.15)
2021	27	179 (0.82)	159 (0.48)	188 (0.99)	118* (0.09)	130 (0.16)
2022	27	170 (0.66)	173 (0.71)	186 (0.95)	118* (0.09)	130 (0.16)

(*Notes.* Numbers in parentheses are prob-values, indicating the probability of a type I error when testing the null hypothesis. ***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004-2008; are 89 at .05 level and 68 at .01 level for 2009-2016; are 98 at .05 level and 75 at .01 level for 2017-2019; are 107 at .05 level and 83 at .01 level for 2020-2022. Iceland is excluded for all years.)

A.3 | Data: ME and GDP (2022)

Table A.8: Military Expenditure (ME) and Gross Domestic Product (GDP) for European Sky Shield Initiative (ESSI) members and non-members.

Country	ESSI	ME (B USD)	GDP (B USD)	ME/GDP (%)
Albania	FALSE	0.29	18.92	1.53
Austria	TRUE	3.63	470.94	0.77
Belgium	TRUE	6.87	583.61	1.18
Bosnia & Herz.	FALSE	0.18	24.53	0.75
Bulgaria	TRUE	1.34	90.35	1.48
Croatia	FALSE	1.31	72.00	1.82
Czechia	TRUE	4.01	290.57	1.38
Denmark	TRUE	5.47	400.17	1.37
Estonia	TRUE	0.81	37.92	2.14
Finland	TRUE	4.82	281.89	1.71
France	TRUE	53.64	2779.09	1.93
Germany	TRUE	55.76	4082.47	1.37
Greece	TRUE	8.10	217.58	3.72
Hungary	TRUE	2.57	177.01	1.45
Ireland	FALSE	1.16	533.14	0.22
Italy	TRUE	33.49	2066.97	1.62
Kosovo	FALSE	0.11	9.35	1.15
Latvia	TRUE	0.85	40.42	2.10
Lithuania	TRUE	1.73	71.01	2.44
Luxembourg	FALSE	0.56	81.64	0.69
Montenegro	FALSE	0.10	6.23	1.57
Netherlands	TRUE	15.61	1009.40	1.55
North Macedonia	FALSE	0.22	13.71	1.64
Norway	TRUE	8.39	593.73	1.41
Poland	TRUE	16.57	689.76	2.40
Portugal	FALSE	3.50	255.20	1.37
Romania	TRUE	5.19	298.89	1.74
Serbia	FALSE	1.43	63.56	2.24
Slovakia	TRUE	1.99	115.58	1.73
Slovenia	TRUE	0.74	60.06	1.22
Spain	FALSE	20.31	1417.80	1.43
Sweden	TRUE	7.72	590.41	1.31
Switzerland	TRUE	6.15	818.43	0.75

Continued on next page

Country	ESSI	ME (B USD)	GDP (B USD)	ME/GDP (%)
Turkey	TRUE	10.64	907.12	1.17
UK	TRUE	68.46	3088.84	2.22
Total	-	353.72	22,258.39	1.59
ESSI + Italy + France	-	324.55	19,762.22	1.67

(*Notes.* The table summarizes Military Expenditure (ME) and Gross Domestic Product (GDP) for ESSI members and non-members in a 35-country set. The ESSI framework accounts for a total of 91.75% of ME and 88.79% of GDP in the 35-country set. Based on data from World Bank (2024) and US Central Intelligence Agency (2024).

A.4 | Alternative Burden-Sharing and Sensitivity Analysis

In the following, the proxy's taken from Sandler and Forbes (1980) are slightly varied and modified. The goal is to understand the sensitivity of the model to changes in certain assumptions and to assess the robustness of its reliability in different scenarios. In addition, a new method called DC is implemented and investigated. Both proxy's have already been analyzed using the Wilcoxon test approach and can be found in A.2. Additionally, the relevance of the Wilcoxon test can be reviewed in Chapter 2.3.2.1.

The factor z_i is part of a country's payoff function u_i, where z_i follows the approximate weighting from Sandler and Forbes (1980).

$$z_i^b = \gamma_{Pop} \frac{\text{POP}_i}{\sum_j \text{POP}_j} + \gamma_{GDP} \frac{\text{GDP}_i}{\sum_j \text{GDP}_j} + \gamma_{Border} \frac{\text{Border}_i}{\sum_j \text{Border}_j} \tag{A.1}$$

We explore two distinct weighting schemes, each offering a unique perspective on the balance of factors:

- **Equal Weighting:**

  The equal weighting scheme assigns equal importance to all three factors:

  $$\gamma_{Pop} = \gamma_{GDP} = \gamma_{Border} = \frac{1}{3}.$$

  This scheme reflects a balanced perspective, ensuring that Population (Pop), GDP, and Border considerations are treated with equal weight. While our primary analysis uses this approach, alternative weightings are discussed in the appendix.

- **Unequal Weighting:**

  The unequal weighting scheme emphasizes the Border factor more heavily:

  $$\gamma_{Pop} = \gamma_{GDP} = \frac{1}{4}, \quad \gamma_{Border} = \frac{1}{2}.$$

  This approach reflects a shift in focus towards geopolitical importance, assigning a smaller influence to economic factors such as Population and GDP. It allows countries to adjust their priorities and strategies, reflecting their own interests and circumstances.

As an alternative to adjusting the weighting in (A.2) a new method involves considering the direct, indirect, or no border with Russia, called the DC. In this method, countries with a direct border receive 3 points, those with an indirect border receive 2 points, and those with no border receive 1 points. The score for each country is then normalized by dividing it by the sum of all the scores. This assumption is based on the perceived threat from proximity to Russia alone, regardless of the length of the border.

$$z_i^d = \gamma_{Pop} \frac{\text{POP}_i}{\sum_j \text{POP}_j} + \gamma_{GDP} \frac{\text{GDP}_i}{\sum_j \text{GDP}_j} + \gamma_{Border} \frac{\text{DC}_i}{\sum_j \text{DC}_j} \tag{A.2}$$

In complete there are four different z_i, z_i^{eb} [2], z_i^{ub} [3], z_i^{ed} [4], the z_i^{ud} [5].

It is important to emphasize that the choice of weighting factors and methods is a subjective one, depending on the goals and perspectives of the country under consideration. This approach allows for a nuanced consideration of different geopolitical aspects and serves as a sensitivity analysis. The use of different weightings makes it possible to assess the sensitivity of the results to changes in the weighting factors and thus the robustness of the model results.

A.5 | Application to ESSI (GDP)

In this section, the individual endowment y_i is redefined as country i's share of total GDP within the country set, replacing the earlier specification based on military expenditure shares in Equation 2.17. We apply the same framework as in Section 2.4.

We now derive the conditions for a stable coalition structure for each coalition size that has emerged since the founding of the ESSI. As shown in Table A.9, none of the observed (partial) coalition structure satisfy the criteria for stable coalitions.

The illustrated Figure A.5, provides a clearer understanding of each country's position relative to others. As mentioned earlier, Finland has a significant impact on the weighting due to its exposed border with Russia, while Germany and the United Kingdom stand out due to their Population and GDP.

---

[2] The index *"eb"* stands for *"equal weighting border"*

[3] The index *"ub"* stands for *"unequal weighting border"*

[4] The index *"ed"* stands for *"equal weighting distance category"*

[5] The index *"ud"* stands for *"unequal weighting distance category."*

Table A.9: Conditions for stable coalition structures of different sizes in a 35-country set

	Values of α_0		
Configuration	Condition 1	Condition 2	Condition 3
z_i^{eb}, 15/35	$\alpha_0 > 3.135$	$\alpha_0 > 2.251$	$\alpha_0 \leq 2.257$
z_i^{eb}, 17/35	$\alpha_0 > 3.287$	$\alpha_0 > 2.438$	$\alpha_0 \leq 2.446$
z_i^{eb}, 19/35	$\alpha_0 > 3.430$	$\alpha_0 > 2.734$	$\alpha_0 \leq 2.743$
z_i^{eb}, 21/35	$\alpha_0 > 3.430$	$\alpha_0 > 3.057$	$\alpha_0 \leq 3.069$
z_i^{eb}, 22/35	$\alpha_0 > 3.430$	$\alpha_0 > 3.296$	$\alpha_0 \leq 3.110$

(*Notes.* The table summarizes the values of α_0 for which each condition is satisfied. The index *"eb"* on z_i refers to the *equal weighting border*, where the Average Benefit Share is calculated as in equation (2.10), using equally weighted determinants: a country's share of total population, share of total GDP, and share of total exposed border with Russia. The configuration 15/35 refers to the founding members of the ESSI. The configuration 15/35 corresponds to the founding members of the ESSI. The larger sets extend this core: 17/35 adds Denmark and Sweden; 19/35 adds Austria and Switzerland; 21/35 includes Turkey and Greece in addition; and 22/35 further includes Poland.)

Table A.10: Scenarios for stable coalition for different configurations with $z_i^{eb}, z_i^{ub}, z_i^{ed}, z_i^{ud}$ for 35 countries

Scenario	$\alpha_0(z_i^{eb})$	$\alpha_0(z_i^{ub})$	$\alpha_0(z_i^{ed})$	$\alpha_0(z_i^{ud})$
1. Current ESSI*	–	–	$[2.712, 2.723]$	$[3.119, 3.131]$
2. ESSI + Italy	$[4.306, 4.329]$	$[5.678, 5.709]$	$[3.542, 3.561]$	$[4.073, 4.095]$
3. ESSI + France	$[4.813, 4.843]$	$[6.348, 6.387]$	$[3.959, 3.983]$	$[4.553, 4.581]$
4. ESSI + Italy + France	$[7.218, 7.280]$	$[9.529, 9.611]$	$[5.933, 5.984]$	$[6.802, 6.861]$

(*Notes.* The table presents the possible stable coalitions and the corresponding values of α_0, presented as an interval, under different configurations of the European Sky Shield Initiative (ESSI). The four different weighting methods considered are: z_i^{eb} (equal weighting border), z_i^{ub} (unequal weighting border), z_i^{ed} (equal weighting distant category), and z_i^{ud} (unequal weighting distant category). For simplicity, square brackets are used here to denote the interval. For further details on the stability conditions, refer to Chapter 2.3.1.*The empirical findings presented are valid up to the end of December 2024; at that point, the coalition consists of 22 members.)

Table A.11: Key indicators of countries in the European Sky Shield Initiative (ESSI), with 22 members plus Italy and France, in a 35-country set

Country	ESSI Member	ABS Components			ABS (%)
		POP (%)	GDP (%)	EBR (%)	
Albania	FALSE	0.44	0.08	0.00	0.18
Austria	TRUE	1.44	2.12	0.00	1.18
Belgium	TRUE	1.86	2.62	0.00	1.49
Bosnia & Herz.	FALSE	0.51	0.11	0.00	0.21
Bulgaria	TRUE	1.03	0.41	0.00	0.48
Croatia	FALSE	0.61	0.32	0.00	0.31
Czechia	TRUE	1.70	1.31	0.00	1.00
Denmark	TRUE	0.94	1.80	0.00	0.91
Estonia	TRUE	0.21	0.17	12.34	4.24
Finland	TRUE	0.88	1.27	49.85	17.33
France	TRUE	10.80	12.49	0.00	7.76
Germany	TRUE	13.31	18.34	0.00	10.55
Greece	TRUE	1.66	0.98	0.00	0.88
Hungary	TRUE	1.53	0.80	0.00	0.78
Ireland	FALSE	0.81	2.40	0.00	1.07
Italy	TRUE	9.36	9.29	0.00	6.22
Kosovo	FALSE	0.28	0.04	0.00	0.11
Latvia	TRUE	0.30	0.18	12.64	4.37
Lithuania	TRUE	0.45	0.32	9.94	3.57
Luxembourg	FALSE	0.10	0.37	0.00	0.16
Montenegro	FALSE	0.10	0.03	0.00	0.04
Netherlands	TRUE	2.81	4.53	0.00	2.45
North Macedonia	FALSE	0.29	0.06	0.00	0.12
Norway	TRUE	0.87	2.67	7.27	3.60
Poland	TRUE	5.85	3.10	7.96	5.64
Portugal	FALSE	1.65	1.15	0.00	0.93
Romania	TRUE	3.03	1.34	0.00	1.46
Serbia	FALSE	1.06	0.29	0.00	0.45
Slovakia	TRUE	0.86	0.52	0.00	0.46
Slovenia	TRUE	0.34	0.27	0.00	0.20
Spain	FALSE	7.59	6.37	0.00	4.65
Sweden	TRUE	1.67	2.65	0.00	1.44
Switzerland	TRUE	1.39	3.68	0.00	1.69

Continued on next page

Country	ESSI Member	ABS Components			ABS (%)
		POP (%)	GDP (%)	EBR (%)	
Turkey	TRUE	13.50	4.08	0.00	5.86
UK	TRUE	10.77	13.88	0.00	8.22
Total	-	100.00	100.00	100.00	100.00
ESSI + Italy + France	-	86.54	88.79	100.00	91.78

(*Notes.* This table presents the participation of countries in the European Sky Shield Initiative (ESSI), with 22 members plus Italy and France, in a 35-country set, based on data from World Bank (2024) and US Central Intelligence Agency (2024).. The contributions here are the share of GDP instead of ME. For each country, Military Expenditure (ME) as a percentage of total ME across countries is displayed. Additional columns include each country's share of the total population (POP), gross domestic product (GDP) share, and exposed border with Russia (EBR) share. The Average Benefit Share (ABS) represents each country's benefit within the ESSI framework. The final row, "ESSI + Italy + France," provides aggregated values for all ESSI members plus Italy and France, with total column sums normalized to 1 for reference.)

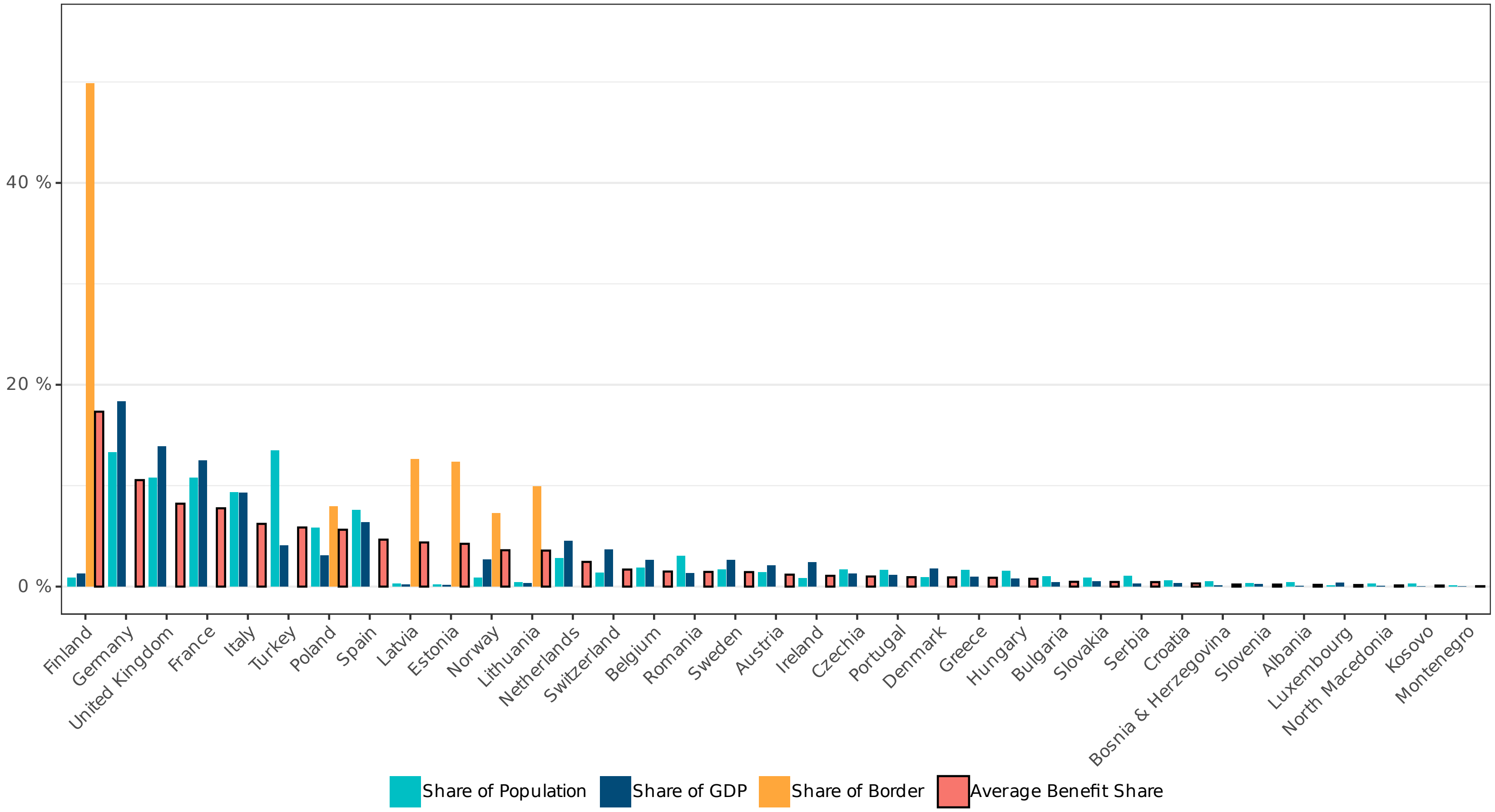


Figure A.5: The figure shows 35 countries on the horizontal axis, ordered by descending values of the Average Benefit Share on the vertical axis. In addition, the determinants such as Population, Gross Domestic Product (GDP), and Exposed Border are also displayed, from which the Average Benefit Share is derived. The calculated Average Benefit Share contributes to each country's payoff function, providing insight into how different input factors are integrated into the payoff function and the subsequent impact on the coalition structure. In this figure, the individual endowment y_i is redefined as country i's share of total GDP within the country set, replacing the earlier specification based on military expenditure shares in Equation 2.17.

A.6 | Application to ESSI (ME)

In this section, the individual endowment y_i is redefined as country i's share of total ME within the country set, as the earlier specification based on military expenditure shares in Equation 2.17. We apply the same framework as in Section 2.4 for different configurations. Before doing that we will have the detailed analysis section that is a part of Section 2.4.3.

A.6.1 | Detailed Analyses

To assess whether the coalition structure is stable, we follow the procedure outlined in Section 2.3.1.1. Having established that the coalition structure under consideration is allowed[6], we first verify Condition 1. This condition requires that each country's expected payoff from participating in the coalition exceeds its selfish payoff—defined as the share of ME. In the present case, we check the columns 'Military Expenditure Share' and 'Expected Payoff'; this inequality holds for all countries.

Next, we turn to Condition 2, which checks whether any country's deviation would place another country in a coalition structure that is not allowed. This condition must hold for all countries and it is sufficient to examine the smallest member of the coalition, Estonia (due to the linear payoff function). If Estonia deviates, the resulting coalition structure positions the United Kingdom as the pivotal country. We examine the column 'Payoff without Estonia' and check whether the payoff for any country is smaller than in the column 'Expected Payoff'. In this case, the structure is not allowed for the UK. Thus, Estonia's deviation would induce a disallowed coalition structure—therefore satisfying Condition 2, as no deviation leads to a stable outcome.

While Condition 3 is satisfied for all, meaning that the payoff from the stable coalition structure is still higher than or equal to the expected payoff of the full cooperative coalition structure. Here, we compare the column 'Payoff in ESSI' with 'Expected Payoff'.

Therefore, all conditions for a stable coalition structure are fulfilled for $\alpha_0 \in (7.750, 7.849]$. This interval represents the range where the coalition remains stable and no country has an incentive to deviate.

---

[6] In the induced game, only those strategy profiles $\sigma = (\sigma_1, \dots, \sigma_N)$ are allowed where each player's payoff $u_i(\sigma_1, \dots, \sigma_N)$ is at least as large as the expected payoff $v_i(p^c)$, where all players act collectively under the coalition structure p^c that maximizes $v(p)$.

Table A.12: Detailed conditions for stable coalition of the ESSI with Italy and France within 35 countries

Country	Military Expend. Share	Average Benefit Share	Multiplier α	Incentive D	Risk R	Prob. τ	Expected Payoff $v_i(p^c)$	Payoff in ESSI	Payoff without Estonia	Cond. 1	Cond. 2	Cond. 3
Austria	0.010250	0.011841	0.091765	0.009309	0.081515	0.102498	0.081670	0.084196	0.084005	✓	✓	✓
Belgium	0.019414	0.014928	0.115692	0.017168	0.096278	0.151331	0.103184	0.106150	0.105910	✓	✓	✓
Bulgaria	0.003777	0.004776	0.037018	0.003637	0.033241	0.098626	0.032920	0.033965	0.033888	✓	✓	✓
Czechia	0.011324	0.010003	0.077521	0.010446	0.066197	0.136295	0.069031	0.071127	0.070966	✓	✓	✓
Denmark	0.015459	0.009119	0.070669	0.014366	0.055211	0.206479	0.063047	0.064841	0.064694	✓	✓	✓
Estonia	0.002293	0.042409	0.328672	0.001539	0.326380	0.004693	0.292175	0.301564	0.300880	✓	✓	✓
Finland	0.013635	0.173323	1.343250	-0.004680	1.329615	0.000000	1.194073	1.232458	1.229666	✓	✓	✓
France	0.151644	0.077612	0.601492	0.060431	0.449849	0.118428	0.545495	0.551881	0.550631	✓	✓	✓
Germany	0.157640	0.105512	0.817715	0.028735	0.660075	0.041717	0.732280	0.750270	0.748570	✓	✓	✓
Greece	0.022913	0.008780	0.068044	0.021354	0.045130	0.321193	0.060988	0.062431	0.062290	✓	✓	✓
Hungary	0.007272	0.007757	0.060118	0.006835	0.052846	0.114525	0.053491	0.055159	0.055034	✓	✓	✓
Italy	0.094680	0.062165	0.481781	0.049065	0.387101	0.112491	0.433407	0.442043	0.441042	✓	✓	✓
Latvia	0.002400	0.043743	0.339010	0.001586	0.336610	0.004690	0.301365	0.311048	0.310344	✓	✓	✓
Lithuania	0.004897	0.035693	0.276622	0.003543	0.271725	0.012870	0.245919	0.253806	0.253231	✓	✓	✓
Netherlands	0.044122	0.024490	0.189795	0.035748	0.145673	0.197043	0.170367	0.174141	0.173746	✓	✓	✓
Norway	0.023715	0.036026	0.279201	0.017094	0.255486	0.062711	0.248609	0.256172	0.255592	✓	✓	✓
Poland	0.046854	0.056358	0.436772	0.026390	0.389917	0.063390	0.389563	0.400747	0.399839	✓	✓	✓
Romania	0.014663	0.014562	0.112857	0.013009	0.098193	0.116982	0.100517	0.103548	0.103314	✓	✓	✓
Slovakia	0.005638	0.004607	0.035706	0.005436	0.030068	0.153118	0.031772	0.032761	0.032687	✓	✓	✓
Slovenia	0.002078	0.002018	0.015638	0.002046	0.013560	0.131102	0.013906	0.014349	0.014316	✓	✓	✓
Sweden	0.021832	0.014395	0.111561	0.019397	0.089729	0.177748	0.099604	0.102359	0.102128	✓	✓	✓
Switzerland	0.017373	0.016904	0.131003	0.015097	0.113629	0.117282	0.116721	0.120197	0.119925	✓	✓	✓
Turkey	0.030094	0.058584	0.454030	0.016430	0.423936	0.037310	0.404117	0.416581	0.415637	✓	✓	✓
UK	0.193553	0.082155	0.636702	0.070317	0.443149	0.136946	0.582869	0.584187	0.582863	✓	✓*	✓

(*Notes.* This table verifies whether the ESSI coalition structure that includes Italy and France satisfies the three formal stability conditions discussed in Section 2.3.1.1. 'Military Expenditure Share' and 'Expected Payoff' are used to check Condition 1, requiring each country's expected payoff to exceed its individual contribution. Condition 2 is assessed by testing whether a deviation—here by the smallest member Estonia—would induce a non-allowed coalition structure for any other member. The checkmark for the UK is marked with an asterisk to indicate that it becomes the pivotal country in the event of Estonia's deviation. Condition 3 ensures that the payoff from participating in ESSI is at least as high as the expected payoff in a fully cooperative structure. The ESSI coalition remains stable in the parameter $\alpha_0 \in (7.750, 7.849]$. Based on data from World Bank (2024) and US Central Intelligence Agency (2024).)

A.6.2 | Additional Analyses

The illustrated Figure A.6 provides a clearer understanding of each country's position relative to others. As mentioned earlier, Finland has a significant impact on the weighting due to its exposed border, while Germany and the United Kingdom stand out due to their Population and ME.

Table A.13: Conditions for stable coalition structures of different sizes in a 35-country set

	Values of α_0		
Configuration	Condition 1	Condition 2	Condition 3
z_i^{eb}, 15/35	$\alpha_0 > 3.356$	$\alpha_0 > 2.185$	$\alpha_0 \leq 2.193$
z_i^{eb}, 17/35	$\alpha_0 > 3.356$	$\alpha_0 > 2.344$	$\alpha_0 \leq 2.353$
z_i^{eb}, 19/35	$\alpha_0 > 3.356$	$\alpha_0 > 2.477$	$\alpha_0 \leq 2.487$
z_i^{eb}, 21/35	$\alpha_0 > 3.893$	$\alpha_0 > 2.771$	$\alpha_0 \leq 2.784$
z_i^{eb}, 22/35	$\alpha_0 > 3.893$	$\alpha_0 > 3.088$	$\alpha_0 \leq 3.104$

(*Notes.* The table summarizes the values of α_0 for which each condition is satisfied. The index *"eb"* on z_i refers to the *equal weighting border*, where the Average Benefit Share is calculated as in equation (2.10), using equally weighted determinants: a country's share of total population, share of total GDP, and share of total exposed border with Russia. The configuration 15/35 refers to the founding members of the ESSI. The configuration 15/35 corresponds to the founding members of the ESSI. The larger sets extend this core: 17/35 adds Denmark and Sweden; 19/35 adds Austria and Switzerland; 21/35 includes Turkey and Greece in addition; and 22/35 further includes Poland.)

Table A.14: Scenarios for stable coalition for different configurations with $z_i^{eb}, z_i^{ub}, z_i^{ed}, z_i^{ud}$ for 35 Countries

Scenario	$\alpha_0(z_i^{eb})$	$\alpha_0(z_i^{ub})$	$\alpha_0(z_i^{ed})$	$\alpha_0(z_i^{ud})$
1. Current ESSI*	–	–	–	–
2. ESSI + Italy	$[4.017, 4.043]$	$[5.271, 5.305]$	$[4.017, 4.043]$	$[3.421, 3.443]$
3. ESSI + France	$[4.904, 4.943]$	$[6.435, 6.486]$	$[4.904, 4.943]$	$[4.177, 4.210]$
4. ESSI + Italy + France	$[7.750, 7.849]$	$[10.170, 10.300]$	$[7.750, 7.849]$	$[6.598, 6.682]$

(*Notes.* The table presents the possible stable coalitions and the corresponding values of α_0, presented as an interval, under different configurations of the European Sky Shield Initiative (ESSI). The four different weighting methods considered are: z_i^{eb} (equal weighting border), z_i^{ub} (unequal weighting border), z_i^{ed} (equal weighting distant category), and z_i^{ud} (unequal weighting distant category). For further details on the stability conditions, refer to Chapter 2.3.1.*The empirical findings presented are valid up to the end of December 2024; at that point, the coalition consists of 22 members.)

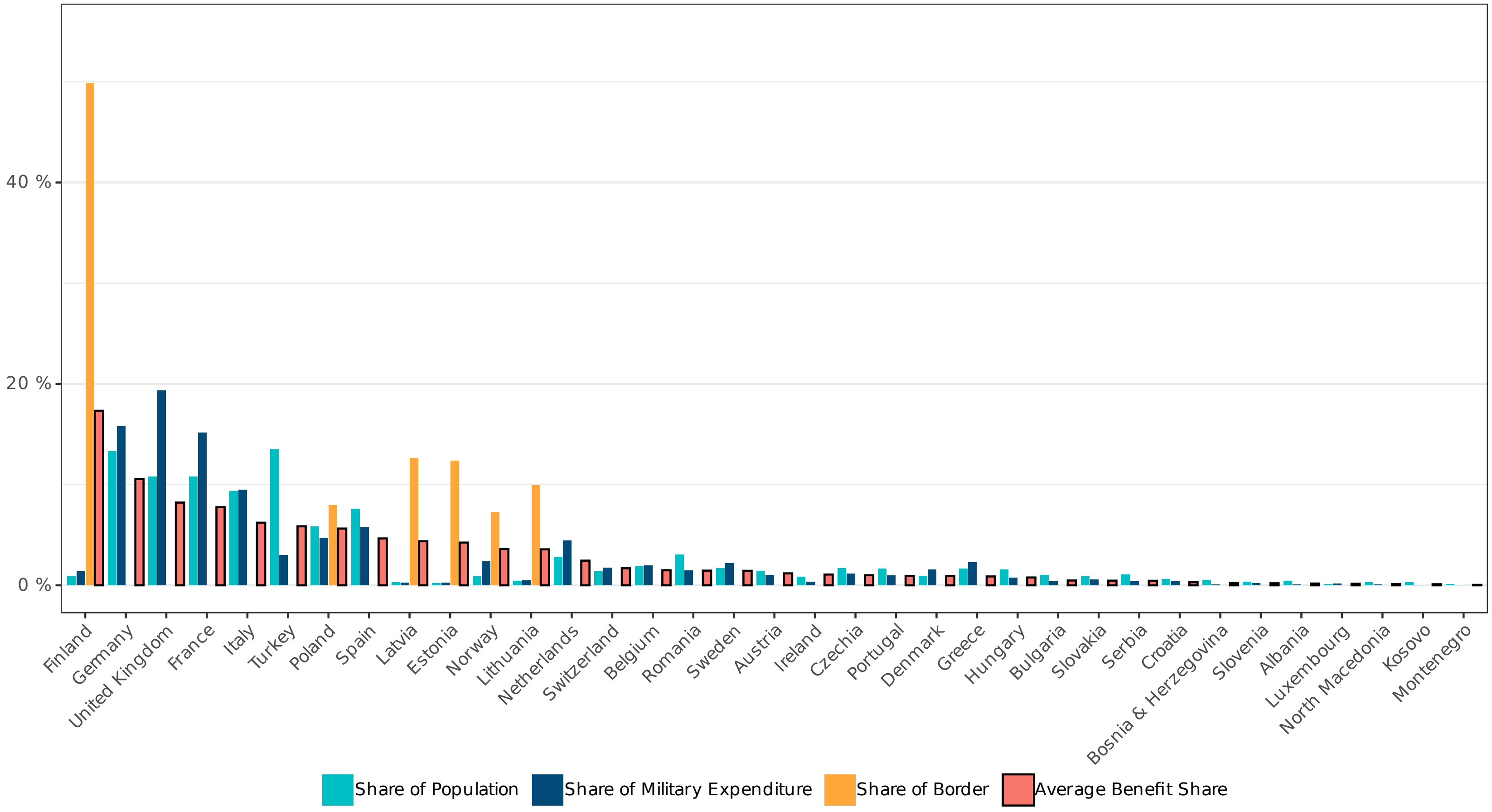


Figure A.6: The figure shows 35 countries on the horizontal axis, ordered by descending payoffs of the Average Benefit Share on the vertical axis. In addition, the determinants such as Population, Military Expenditure (ME), and Exposed Border are also displayed. The calculated Average Benefit Share contributes to each country's payoff function, providing insight into how different input factors are integrated into the payoff function and the subsequent impact on the coalition structure.

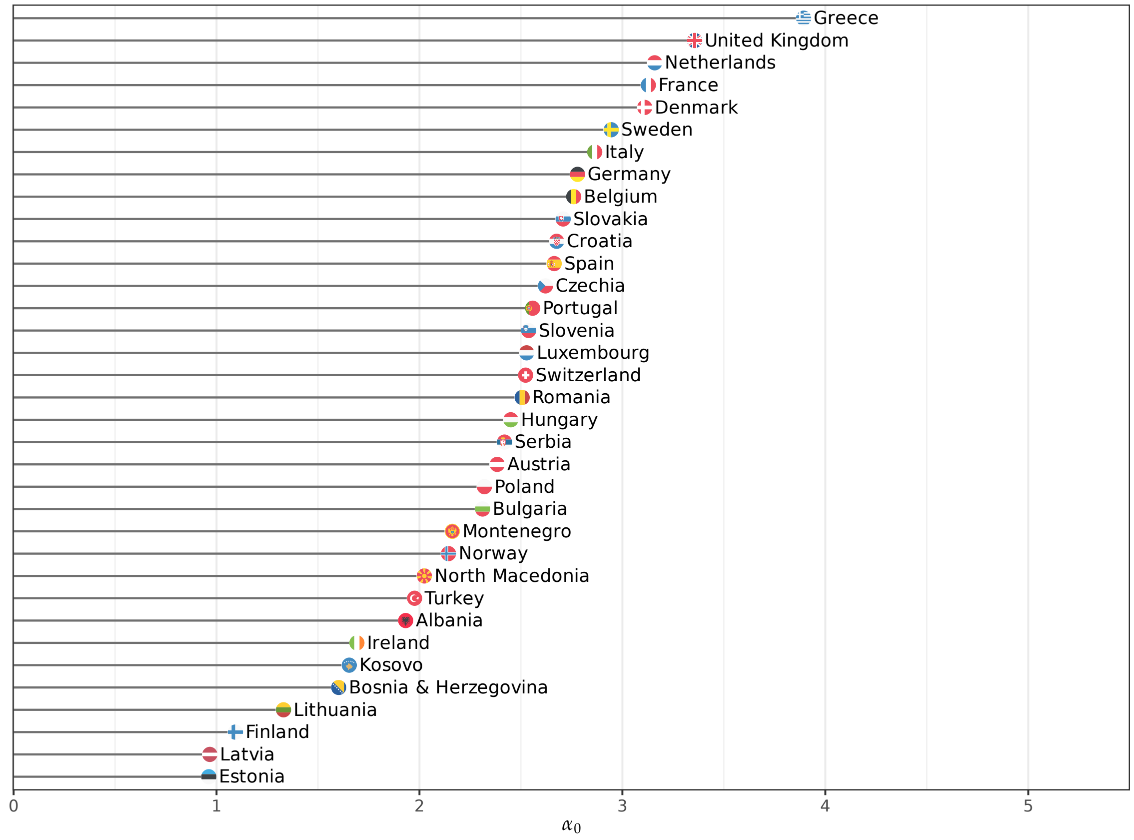


Figure A.7: The figure plots the threat factor α_0 on the horizontal axis, with countries listed on the vertical axis. The horizontal line represents the exogenous threat payoff α_0 of a country at which the expected value $v_i(p^c)$ exceeds the contribution x_i.

Figure A.7 clearly shows that some countries benefit more from participating in the coalition than others. In particular, countries with a common border with Russia benefit from the coalition at a threat factor between 1 and 2. Countries without a common border with Russia, on the other hand, require a higher threat factor for the benefit from the coalition to exceed the initial endowment.

These differences can be explained by the geopolitical situation and the threat factor. Countries with a common border with Russia can benefit more from security advantages due to their direct proximity. In such cases, the expected payoff $v_i(p^c)$ outweighs the contribution x_i, which is the endowment y_i, at an early stage.

On the other hand, countries without a border with Russia require a higher threat factor to achieve a comparable benefit. This may be due to a more nuanced threat assessment and lower immediate security relevance.

The results presented provide insights into the different dynamics that can occur when participating in a coalition and highlight the role of geopolitical circumstances in influencing coalition payoff.

A.6.3 | Scenario: 'Distance Category'

In this section, the 'EBR' determinant is replaced with the 'DC', and we replicate the A.7 and 2.5.

Table A.15: Key indicators of countries in the European Sky Shield Initiative (ESSI), with 22 members plus Italy and France, in a 35-country set

Country	ESSI Member	ME (%)	ABS Components			ABS (%)
			POP (%)	GDP (%)	DC (%)	
Albania	FALSE	0.08	0.44	0.08	1.82	0.78
Austria	TRUE	1.02	1.44	2.12	1.82	1.79
Belgium	TRUE	1.94	1.86	2.62	1.82	2.10
Bosnia & Herz.	FALSE	0.05	0.51	0.11	1.82	0.81
Bulgaria	TRUE	0.38	1.03	0.41	1.82	1.08
Croatia	FALSE	0.37	0.61	0.32	1.82	0.92
Czechia	TRUE	1.13	1.70	1.31	3.64	2.21
Denmark	TRUE	1.55	0.94	1.80	3.64	2.12
Estonia	TRUE	0.23	0.21	0.17	5.45	1.95
Finland	TRUE	1.36	0.88	1.27	5.45	2.53
France	TRUE	15.16	10.80	12.49	1.82	8.37
Germany	TRUE	15.76	13.31	18.34	3.64	11.76
Greece	TRUE	2.29	1.66	0.98	1.82	1.48
Hungary	TRUE	0.73	1.53	0.80	3.64	1.99
Ireland	FALSE	0.33	0.81	2.40	1.82	1.68
Italy	TRUE	9.47	9.36	9.29	1.82	6.82
Kosovo	FALSE	0.03	0.28	0.04	1.82	0.71
Latvia	TRUE	0.24	0.30	0.18	5.45	1.98
Lithuania	TRUE	0.49	0.45	0.32	5.45	2.07
Luxembourg	FALSE	0.16	0.10	0.37	1.82	0.76
Montenegro	FALSE	0.03	0.10	0.03	1.82	0.65
Netherlands	TRUE	4.41	2.81	4.53	1.82	3.06
North Macedonia	FALSE	0.06	0.29	0.06	1.82	0.72
Norway	TRUE	2.37	0.87	2.67	5.45	3.00
Poland	TRUE	4.69	5.85	3.10	5.45	4.80
Portugal	FALSE	0.99	1.65	1.15	1.82	1.54
Romania	TRUE	1.47	3.03	1.34	3.64	2.67
Serbia	FALSE	0.40	1.06	0.29	1.82	1.05
Slovakia	TRUE	0.56	0.86	0.52	3.64	1.67

Continued on next page

Country	ESSI Member	ME (%)	ABS Components			ABS (%)
			POP (%)	GDP (%)	DC (%)	
Slovenia	TRUE	0.21	0.34	0.27	1.82	0.81
Spain	FALSE	5.74	7.59	6.37	1.82	5.26
Sweden	TRUE	2.18	1.67	2.65	3.64	2.65
Switzerland	TRUE	1.74	1.39	3.68	1.82	2.30
Turkey	TRUE	3.01	13.50	4.08	3.64	7.07
UK	TRUE	19.36	10.77	13.88	1.82	8.82
Total	-	100.00	100.00	100.00	100.00	100.00
ESSI + Italy + France	-	91.75	86.54	88.79	100.00	85.10

(*Notes.* This table presents the participation of countries in the European Sky Shield Initiative (ESSI), with 22 members plus Italy and France, in a 35-country set, based on data from World Bank (2024) and US Central Intelligence Agency (2024). For each country, Military Expenditure (ME) as a percentage of total ME across countries is displayed. Additional columns include each country's share of the total population (POP), gross domestic product (GDP) share, and Distance Category (DC). The Average Benefit Share (ABS) represents each country's benefit within the ESSI framework. The final row, "ESSI + Italy + France," provides aggregated values for all ESSI members plus Italy and France, with total column sums normalized to 1 for reference.)

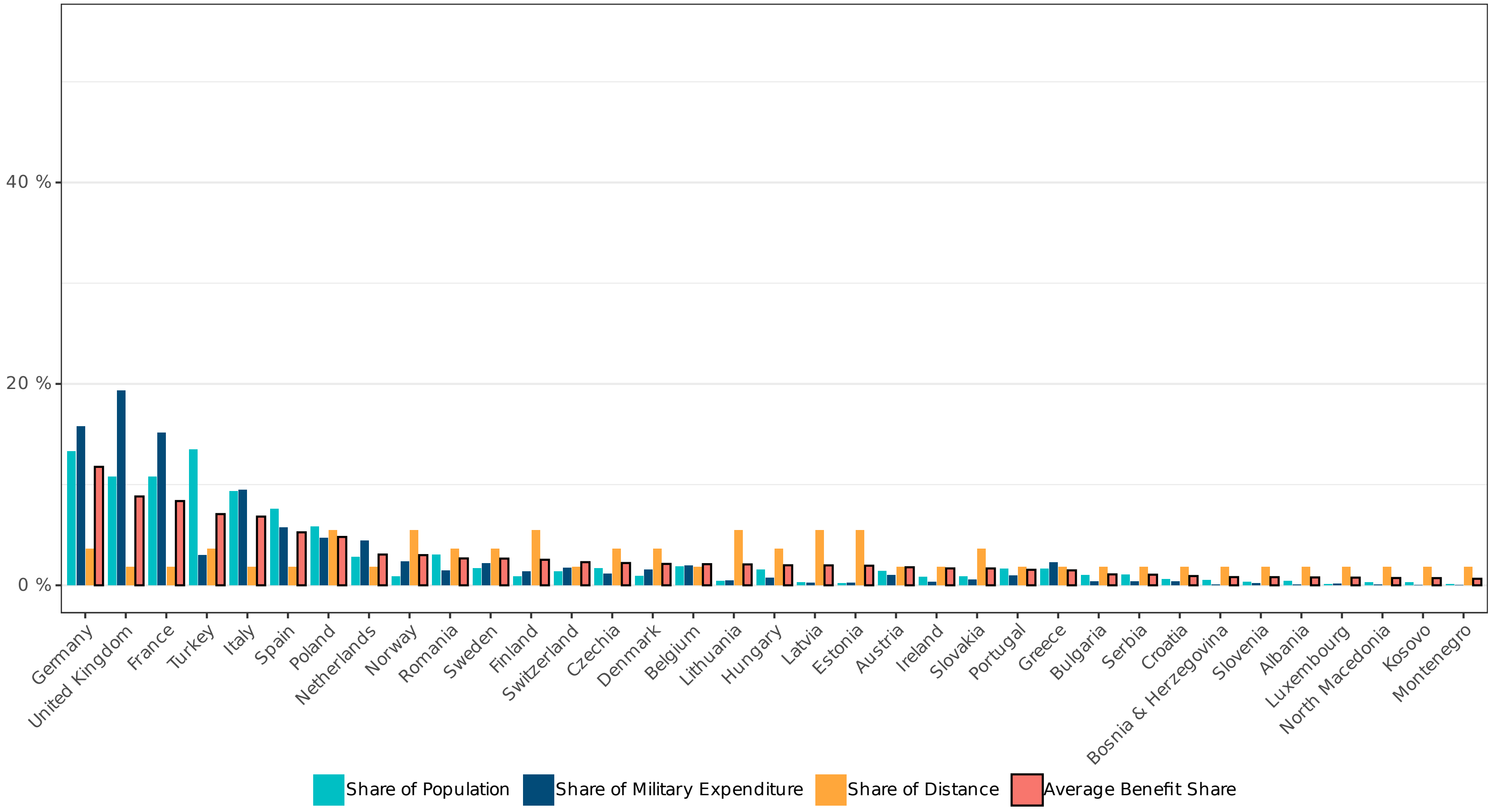


Figure A.8: The figure shows 35 countries on the horizontal axis, ordered by descending payoffs of the Average Benefit Share on the vertical axis. In addition, the determinants such as Population, Military Expenditure (ME), and Distance Category are also displayed, from which the Average Benefit Share is derived. The calculated Average Benefit Share contributes to each country's payoff function, providing insight into how different input factors are integrated into the payoff function and the subsequent impact on the coalition structure.

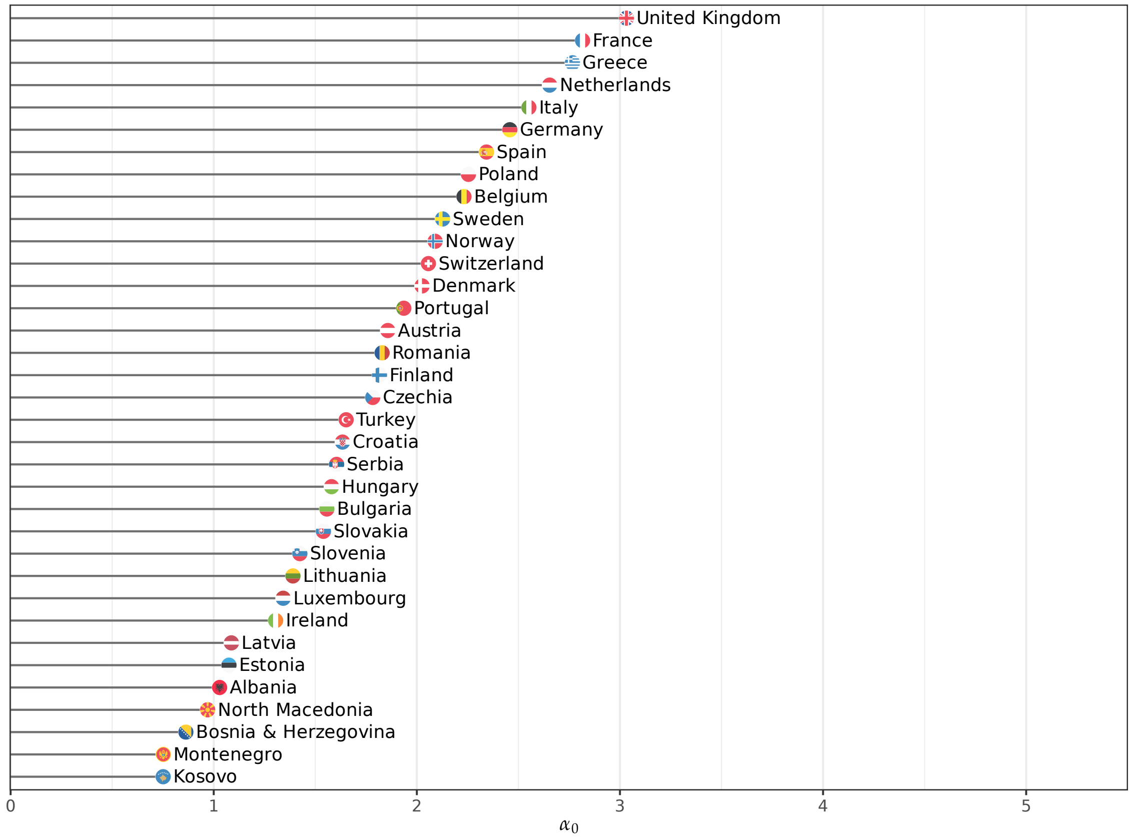


Figure A.9: The figure plots the threat factor α_0 on the horizontal axis, with countries listed on the vertical axis. The horizontal line represents the exogenous threat value α_0 of a country at which the expected payoff $v_i(p^c)$ exceeds the contribution x_i.

A.7 | Albania and Portugal Join ESSI as of February 2025

Over the course of this research, the ESSI coalition has evolved, prompting us to periodically revisit and validate the findings in light of theoretical expectations. This appendix presents a country configuration not included in the main analysis. According to sources, the ESSI consisted of 22 members as of December 2024. Notably, Poland was already counted as a member, consistent with statements by Prime Minister Tusk. However, Poland is still not officially a member and no formal changes occurred over the following year. In contrast, Albania and Portugal officially joined the initiative in early 2025.

To ensure that our conclusions remain robust, we extended the analysis to incorporate this new composition. The results presented here are consistent with the theoretical framework established earlier. Since the methodology and interpretation have already been discussed in detail, the following tables are provided primarily for interested readers and are not elaborated further. For completeness, we also replicated the analysis using the alternative specification of 'DC' instead of 'EBR', and substituted GDP for ME as the contribution.

A.7.1 | Application to ESSI (ME) as of February 2025

Table A.16: Scenarios for stable coalition for different configurations with $z_i^{eb}, z_i^{ub}, z_i^{ed}, z_i^{ud}$ for 35 countries

Scenario	$\alpha_0(z_i^{eb})$	$\alpha_0(z_i^{ub})$	$\alpha_0(z_i^{ed})$	$\alpha_0(z_i^{ud})$
1. Current ESSI*	–	–	–	–
2. ESSI + Italy	$[4.176, 4.187]$	$[5.479, 5.493]$	$[3.557, 3.565]$	$[4.123, 4.133]$
3. ESSI + France	$[5.143, 5.159]$	$[6.748, 6.770]$	$[4.380, 4.394]$	$[5.077, 4.093]$
4. ESSI + Italy + France	$[8.364, 8.408]$	$[10.976, 11.034]$	$[7.120, 7.158]$	$[8.254, 8.297]$

(*Notes.* The table presents the possible stable coalitions and the corresponding values of α_0, presented as an interval, under different configurations of the European Sky Shield Initiative (ESSI). The four different weighting methods considered are: z_i^{eb} (equal weighting border), z_i^{ub} (unequal weighting border), z_i^{ed} (equal weighting distant category), and z_i^{ud} (unequal weighting distant category). For further details on the stability conditions, refer to Chapter 2.3.1.*The empirical findings presented are valid up to the end of February 2025; at that point, the coalition consists of 23 members.)

Table A.17: Determinants of the 25 participants, the computed average benefit share, multiplier α, and payoff for the threat factor $\alpha_0 = 6.385$ in the stable coalition with a country set of 35

Country	ME (%)	ABS Determinants			ABS (%)	Multiplier α_i	Payoff u_i
		POP (%)	GDP (%)	EBR (%)			
Albania	0.08	0.44	0.08	0.00	0.18	0.0112	0.0099
Austria	1.02	1.44	2.12	0.00	1.18	0.0756	0.0666
Belgium	1.94	1.86	2.62	0.00	1.49	0.0953	0.0840
Bulgaria	0.38	1.03	0.41	0.00	0.48	0.0305	0.0269
Czechia	1.13	1.70	1.31	0.00	1.00	0.0639	0.0563
Denmark	1.55	0.94	1.80	0.00	0.91	0.0582	0.0513
Estonia	0.23	0.21	0.17	12.34	4.24	0.2708	0.2387
Finland	1.36	0.88	1.27	49.85	17.33	1.1067	0.9754
France	15.16	10.80	12.49	0.00	7.76	0.4956	0.4368
Germany	15.76	13.31	18.34	0.00	10.55	0.6737	0.5938
Greece	2.29	1.66	0.98	0.00	0.88	0.0561	0.0494
Hungary	0.73	1.53	0.80	0.00	0.78	0.0495	0.0437
Italy	9.47	9.36	9.29	0.00	6.22	0.3969	0.3498
Latvia	0.24	0.30	0.18	12.64	4.37	0.2793	0.2462
Lithuania	0.49	0.45	0.32	9.94	3.57	0.2279	0.2009
Netherlands	4.41	2.81	4.53	0.00	2.45	0.1564	0.1378
Norway	2.37	0.87	2.67	7.27	3.60	0.2300	0.2027
Portugal	0.99	1.65	1.15	0.00	0.93	0.0596	0.0525
Romania	1.47	3.03	1.34	0.00	1.46	0.0930	0.0819
Slovakia	0.56	0.86	0.52	0.00	0.46	0.0294	0.0259
Slovenia	0.21	0.34	0.27	0.00	0.20	0.0129	0.0114
Sweden	2.18	1.67	2.65	0.00	1.44	0.0919	0.0810
Switzerland	1.74	1.39	3.68	0.00	1.69	0.1079	0.0951
Turkey	3.01	13.50	4.08	0.00	5.86	0.3741	0.3297
UK	19.36	10.77	13.88	0.00	8.22	0.5246	0.4623
Total	88.14	82.79	86.92	92.04	87.25	5.5708	4.9100

(*Notes.* We examine the Stable Coalition . The last column represents the relative payoff of the coalition, indicating the payoff each country receives within the ESSI. The sums of the Multiplier α_i and payoff columns should be understood as cumulative in absolute terms, due to the non-excludability of the provided Supranational Public Good, whereas the other columns sum up to 100% for the 35-country set. Based on data from the World Bank (2024) and the US Central Intelligence Agency (2024).)

Table A.18: Key indicators of countries in the European Sky Shield Initiative (ESSI), with 23 members plus Italy and France, in a 35-country set

Country	ESSI Member	ME (%)	ABS Components			ABS (%)
			POP (%)	GDP (%)	EBR (%)	
Albania	TRUE	0.08	0.44	0.08	0.00	0.18
Austria	TRUE	1.02	1.44	2.12	0.00	1.18
Belgium	TRUE	1.94	1.86	2.62	0.00	1.49
Bosnia & Herz.	FALSE	0.05	0.51	0.11	0.00	0.21
Bulgaria	TRUE	0.38	1.03	0.41	0.00	0.48
Croatia	FALSE	0.37	0.61	0.32	0.00	0.31
Czechia	TRUE	1.13	1.70	1.31	0.00	1.00
Denmark	TRUE	1.55	0.94	1.80	0.00	0.91
Estonia	TRUE	0.23	0.21	0.17	12.34	4.24
Finland	TRUE	1.36	0.88	1.27	49.85	17.33
France	TRUE	15.16	10.80	12.49	0.00	7.76
Germany	TRUE	15.76	13.31	18.34	0.00	10.55
Greece	TRUE	2.29	1.66	0.98	0.00	0.88
Hungary	TRUE	0.73	1.53	0.80	0.00	0.78
Ireland	FALSE	0.33	0.81	2.40	0.00	1.07
Italy	TRUE	9.47	9.36	9.29	0.00	6.22
Kosovo	FALSE	0.03	0.28	0.04	0.00	0.11
Latvia	TRUE	0.24	0.30	0.18	12.64	4.37
Lithuania	TRUE	0.49	0.45	0.32	9.94	3.57
Luxembourg	FALSE	0.16	0.10	0.37	0.00	0.16
Montenegro	FALSE	0.03	0.10	0.03	0.00	0.04
Netherlands	TRUE	4.41	2.81	4.53	0.00	2.45
North Macedonia	FALSE	0.06	0.29	0.06	0.00	0.12
Norway	TRUE	2.37	0.87	2.67	7.27	3.60
Poland	FALSE	4.69	5.85	3.10	7.96	5.64
Portugal	TRUE	0.99	1.65	1.15	0.00	0.93
Romania	TRUE	1.47	3.03	1.34	0.00	1.46
Serbia	FALSE	0.40	1.06	0.29	0.00	0.45
Slovakia	TRUE	0.56	0.86	0.52	0.00	0.46
Slovenia	TRUE	0.21	0.34	0.27	0.00	0.20
Spain	FALSE	5.74	7.59	6.37	0.00	4.65
Sweden	TRUE	2.18	1.67	2.65	0.00	1.44
Switzerland	TRUE	1.74	1.39	3.68	0.00	1.69

Continued on next page

Country	ESSI Member	ME (%)	ABS Components			ABS (%)
			POP (%)	GDP (%)	EBR (%)	
Turkey	TRUE	3.01	13.50	4.08	0.00	5.86
UK	TRUE	19.36	10.77	13.88	0.00	8.22
Total	-	100.00	100.00	100.00	100.00	100.00
ESSI + Italy + France	-	88.14	82.79	86.92	92.04	87.25

(*Notes.* This table presents the participation of countries in the European Sky Shield Initiative (ESSI), with 23 members plus Italy and France, in a 35-country set, based on data from World Bank (2024) and US Central Intelligence Agency (2024). For each country, Military Expenditure (ME) as a percentage of total ME across countries is displayed. Additional columns include each country's share of the total population (POP), gross domestic product (GDP) share, and exposed border with Russia (EBR) share. The Average Benefit Share (ABS) represents each country's benefit within the ESSI framework. The final row, "ESSI + Italy + France," provides aggregated values for all ESSI members plus Italy and France, with total column sums normalized to 1 for reference.)

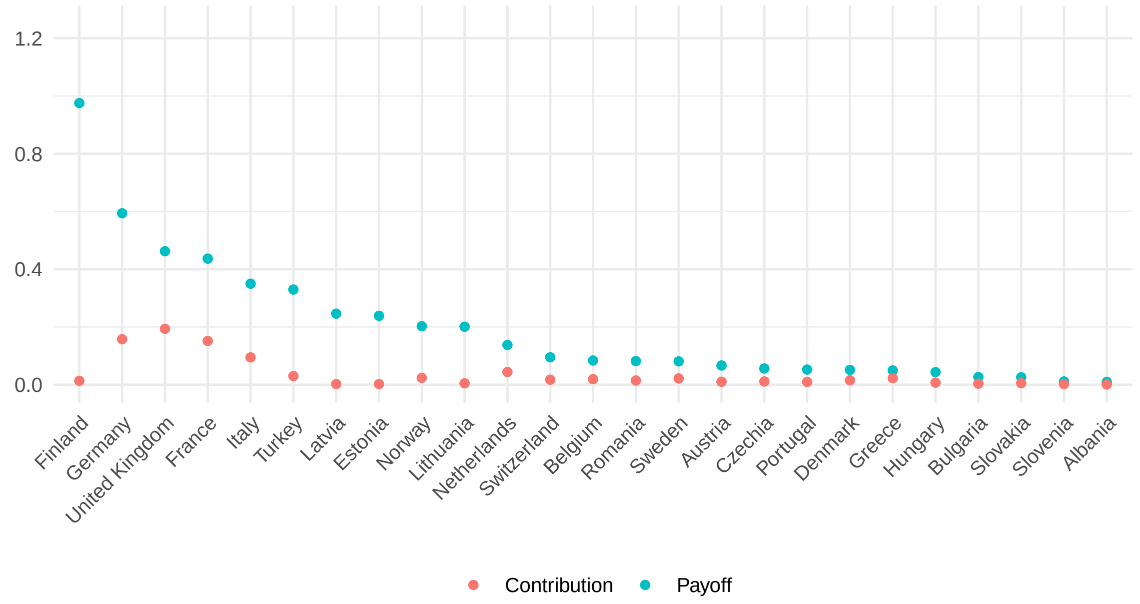


Figure A.10: The figure plots the 25 participant countries on the horizontal axis, with their contribution and received payoff on the vertical axis given a threat factor $\alpha_0 = 6.385$. Each country's payoff derived from its economic, demographic, and geopolitical factors. Higher payoff values correspond to countries with larger exposed borders with Russia or with greater economic and demographic weights, indicating their higher relative benefits from ESSI participation.

A.7.2 | Application to ESSI (GDP) as of February 2025

This is the replication of A.5 with Albania and Portugal as members. In this section, the individual endowment y_i is redefined as country i's share of total GDP within the country set, replacing the earlier specification based on military expenditure shares in Equation 2.17.

Table A.19: Scenarios for stable coalition for different configurations with $z_i^{eb}, z_i^{ub}, z_i^{ed}, z_i^{ud}$ for 35 countries

Scenario	$\alpha_0(z_i^{eb})$	$\alpha_0(z_i^{ub})$	$\alpha_0(z_i^{ed})$	$\alpha_0(z_i^{ud})$
1. Current ESSI*	–	–	–	–
2. ESSI + Italy	$[4.067, 4.077]$	$[5.363, 5.376]$	$[3.345, 3.353]$	$[3.847, 3.856]$
3. ESSI + France	$[4.517, 4.529]$	$[5.957, 5.973]$	$[3.715, 3.725]$	$[4.273, 4.284]$
4. ESSI + Italy + France	$[6.620, 6.645]$	$[8.740, 8.773]$	$[5.442, 5.463]$	$[6.239, 6.263]$

(*Notes.* The table presents the possible stable coalitions and the corresponding values of α_0, presented as an interval, under different configurations of the European Sky Shield Initiative (ESSI). The four different weighting methods considered are: z_i^{eb} (equal weighting border), z_i^{ub} (unequal weighting border), z_i^{ed} (equal weighting distant category), and z_i^{ud} (unequal weighting distant category). For further details on the stability conditions, refer to Chapter 2.3.1.*The empirical findings presented are valid up to the end of February 2025; at that point, the coalition consists of 23 members.)

Table A.20: Key indicators of countries in the European Sky Shield Initiative (ESSI), with 22 members plus Italy and France, in a 35-country set

Country	ESSI Member	ABS Components			ABS (%)
		POP (%)	GDP (%)	EBR (%)	
Albania	TRUE	0.44	0.08	0.00	0.18
Austria	TRUE	1.44	2.12	0.00	1.18
Belgium	TRUE	1.86	2.62	0.00	1.49
Bosnia & Herz.	FALSE	0.51	0.11	0.00	0.21
Bulgaria	TRUE	1.03	0.41	0.00	0.48
Croatia	FALSE	0.61	0.32	0.00	0.31
Czechia	TRUE	1.70	1.31	0.00	1.00
Denmark	TRUE	0.94	1.80	0.00	0.91
Estonia	TRUE	0.21	0.17	12.34	4.24
Finland	TRUE	0.88	1.27	49.85	17.33
France	TRUE	10.80	12.49	0.00	7.76

Continued on next page

Country	ESSI Member	ABS Components			ABS (%)
		POP (%)	GDP (%)	EBR (%)	
Germany	TRUE	13.31	18.34	0.00	10.55
Greece	TRUE	1.66	0.98	0.00	0.88
Hungary	TRUE	1.53	0.80	0.00	0.78
Ireland	FALSE	0.81	2.40	0.00	1.07
Italy	TRUE	9.36	9.29	0.00	6.22
Kosovo	FALSE	0.28	0.04	0.00	0.11
Latvia	TRUE	0.30	0.18	12.64	4.37
Lithuania	TRUE	0.45	0.32	9.94	3.57
Luxembourg	FALSE	0.10	0.37	0.00	0.16
Montenegro	FALSE	0.10	0.03	0.00	0.04
Netherlands	TRUE	2.81	4.53	0.00	2.45
North Macedonia	FALSE	0.29	0.06	0.00	0.12
Norway	TRUE	0.87	2.67	7.27	3.60
Poland	FALSE	5.85	3.10	7.96	5.64
Portugal	TRUE	1.65	1.15	0.00	0.93
Romania	TRUE	3.03	1.34	0.00	1.46
Serbia	FALSE	1.06	0.29	0.00	0.45
Slovakia	TRUE	0.86	0.52	0.00	0.46
Slovenia	TRUE	0.34	0.27	0.00	0.20
Spain	FALSE	7.59	6.37	0.00	4.65
Sweden	TRUE	1.67	2.65	0.00	1.44
Switzerland	TRUE	1.39	3.68	0.00	1.69
Turkey	TRUE	13.50	4.08	0.00	5.86
UK	TRUE	10.77	13.88	0.00	8.22
Total	-	100.00	100.00	100.00	100.00
ESSI + Italy + France	-	82.79	86.92	92.04	87.25

(*Notes.* This table presents the participation of countries in the European Sky Shield Initiative (ESSI), with 23 members plus Italy and France, in a 35-country set, based on data from World Bank (2024) and US Central Intelligence Agency (2024). The contributions here are the share of GDP instead of ME. For each country, Military Expenditure (ME) as a percentage of total ME across countries is displayed. Additional columns include each country's share of the total population (POP), gross domestic product (GDP) share, and exposed border with Russia (EBR) share. The Average Benefit Share (ABS) represents each country's benefit within the ESSI framework. The final row, "ESSI + Italy + France," provides aggregated values for all ESSI members plus Italy and France, with total column sums normalized to 1 for reference.)

A.7.3 | Scenario: 'Distance Category' as of February 2025

This is the replication of A.6.3 with Albania and Portugal as members. In this section, the 'EBR' determinant is replaced with the 'DC'.

Table A.21: Key Indicators of countries in the European Sky Shield Initiative (ESSI), with 23 members plus Italy and France, in a 35-country set

Country	ESSI Member	ME (%)	ABS Components			ABS (%)
			POP (%)	GDP (%)	DC (%)	
Albania	TRUE	0.08	0.44	0.08	1.82	0.78
Austria	TRUE	1.02	1.44	2.12	1.82	1.79
Belgium	TRUE	1.94	1.86	2.62	1.82	2.10
Bosnia & Herz.	FALSE	0.05	0.51	0.11	1.82	0.81
Bulgaria	TRUE	0.38	1.03	0.41	1.82	1.08
Croatia	FALSE	0.37	0.61	0.32	1.82	0.92
Czechia	TRUE	1.13	1.70	1.31	3.64	2.21
Denmark	TRUE	1.55	0.94	1.80	3.64	2.12
Estonia	TRUE	0.23	0.21	0.17	5.45	1.95
Finland	TRUE	1.36	0.88	1.27	5.45	2.53
France	TRUE	15.16	10.80	12.49	1.82	8.37
Germany	TRUE	15.76	13.31	18.34	3.64	11.76
Greece	TRUE	2.29	1.66	0.98	1.82	1.48
Hungary	TRUE	0.73	1.53	0.80	3.64	1.99
Ireland	FALSE	0.33	0.81	2.40	1.82	1.68
Italy	TRUE	9.47	9.36	9.29	1.82	6.82
Kosovo	FALSE	0.03	0.28	0.04	1.82	0.71
Latvia	TRUE	0.24	0.30	0.18	5.45	1.98
Lithuania	TRUE	0.49	0.45	0.32	5.45	2.07
Luxembourg	FALSE	0.16	0.10	0.37	1.82	0.76
Montenegro	FALSE	0.03	0.10	0.03	1.82	0.65
Netherlands	TRUE	4.41	2.81	4.53	1.82	3.06
North Macedonia	FALSE	0.06	0.29	0.06	1.82	0.72
Norway	TRUE	2.37	0.87	2.67	5.45	3.00
Poland	FALSE	4.69	5.85	3.10	5.45	4.80
Portugal	TRUE	0.99	1.65	1.15	1.82	1.54
Romania	TRUE	1.47	3.03	1.34	3.64	2.67
Serbia	FALSE	0.40	1.06	0.29	1.82	1.05
Slovakia	TRUE	0.56	0.86	0.52	3.64	1.67

Continued on next page

Country	ESSI Member	ME (%)	ABS Components			ABS (%)
			POP (%)	GDP (%)	DC (%)	
Slovenia	TRUE	0.21	0.34	0.27	1.82	0.81
Spain	FALSE	5.74	7.59	6.37	1.82	5.26
Sweden	TRUE	2.18	1.67	2.65	3.64	2.65
Switzerland	TRUE	1.74	1.39	3.68	1.82	2.30
Turkey	TRUE	3.01	13.50	4.08	3.64	7.07
UK	TRUE	19.36	10.77	13.88	1.82	8.82
Total	-	100.00	100.00	100.00	100.00	100.00
ESSI + Italy + France	-	88.14	82.79	86.92	78.18	82.63

(*Notes.* This table presents the participation of countries in the European Sky Shield Initiative (ESSI), with 23 members plus Italy and France, in a 35-country set, based on data from World Bank (2024) and US Central Intelligence Agency (2024).. For each country, Military Expenditure (ME) as a percentage of total ME across countries is displayed. Additional columns include each country's share of the total population (POP), gross domestic product (GDP) share, and Distance Category (DC). The Average Benefit Share (ABS) represents each country's benefit within the ESSI framework. The final row, "ESSI + Italy + France," provides aggregated values for all ESSI members plus Italy and France, with total column sums normalized to 1 for reference.)

CHAPTER 3

This part is based on the joint work:

> ***European NATO Burden Sharing 1993-2022: New Perspectives***,
> by Resul Zoroğlu and Noah Oerther.

ABSTRACT

This paper investigates how defense burdens are shared among European NATO members from 1993 to 2022. Motivated by repeated US concerns over unequal contributions within the alliance, we ask whether European NATO members have persistently free-ridden on the efforts of others. To address this, we introduce three novel measurement methods that capture burden-sharing. Using Spearman rank correlations and Wilcoxon signed-rank tests, we find no evidence of persistent exploitation over the 1993-2022 period within European NATO members. Building on these results, we propose new burden-sharing methods specifically designed for European NATO members to improve concordance between defense burdens and benefits.

Chapter 3

European NATO Burden Sharing 1993-2022

3.1 Introduction

In contrast to earlier assessments by Sandler and Shimizu (2014), which described a declining threat from Russia in the post–Cold War period, recent developments have fundamentally altered the European security landscape. The annexation of Crimea in 2014 and Russia's full-scale invasion of Ukraine in 2022 have triggered a sharp reversal in defense policy across Europe. Many European countries substantially increased their defense expenditures after decades of underinvestment (European Commission, 2022). To address longstanding inefficiencies resulting from fragmented national air defense systems and to enhance collective deterrence, 14 NATO member states and Finland launched the European Sky Shield Initiative (ESSI) in October 2022. This initiative aims to coordinate multinational procurement and deployment of air defense systems, representing a new form of burden-sharing within European NATO.[1]

The emergence of such initiatives must be understood in light of the broader historical struggle of NATO with defense burden-sharing. Since its inception in 1949, NATO has grappled with the persistent challenge of equitable burden-sharing among its members. The original twelve-member alliance was primarily a response to Soviet expansion, but the mission and composition of NATO have evolved significantly, particularly since the end of the Cold War. Enlargement episodes between 1999 and 2020 increased membership from 16 to 30 countries, amplifying alliance heterogeneity in terms of economic capacity, military capability, geographic proximity to threats, and security priorities. Such heterogeneity complicates collective decision-making and underscores longstanding concerns regarding free-riding and uneven burden distribution.

This study systematically explores burden-sharing dynamics, specifically within European NATO members from 1993 to 2022. This period was marked by NATO enlargement, changing US security commitments in Europe, and the resurgence of Russian aggression exemplified by the annexation of Crimea and the war in Ukraine. We utilize an empirical framework based on the Olson and Zeckhauser (1966) exploitation hypothesis and extend

---

[1] NATO was founded in 1949 by 12 countries, including Belgium, Canada, Denmark, France, Iceland, Italy, Luxembourg, the Netherlands, Norway, Portugal, the United Kingdom, and the United States. The following countries joined later: Greece and Turkey (1952); Germany (1955); Spain (1982); Czech Republic, Hungary, and Poland (1999); Bulgaria, Estonia, Latvia, Lithuania, Romania, Slovakia, and Slovenia (2004); Albania and Croatia (2009); Montenegro (2017); North Macedonia (2020); Finland (2023); and Sweden (2024). The United States and Canada, although founding members, are excluded from the list of European NATO countries (North Atlantic Treaty Organization, 2025)

analyses by Sandler and Shimizu (2014) by incorporating updated panel data on GDP, military expenditures, population size, and proximity-based threat assessments. Through the application of Spearman rank correlation tests and Wilcoxon signed-rank tests, we assess whether European allies' defense contributions align with their respective ability to pay and perceived security benefits.

When focusing on European NATO members, our analysis indicates limited evidence of persistent exploitation of wealthier allies by poorer ones in early years. However, significant deviations from burden-sharing emerge post-2004 and intensify after 2014, aligning with periods of heightened Russian threats and changing US policies. Notably, countries such as Germany, France, and the United Kingdom consistently appear as overcontributors, whereas poorer and newer NATO members often undercontribute relative to their benefit shares. These imbalances are less severe than compared to NATO as a whole due to the exclusion of disproportionately high US spending. However, they reveal intra-European disparities and increasing free-riding tendencies.

The findings underscore important policy challenges facing European defense cooperation, particularly given recent US signals toward reducing its security commitments in Europe. Addressing these disparities will be crucial for sustaining NATO's cohesion and effectiveness. By focusing on European NATO members and updating the empirical record through 2022, this paper provides a more nuanced understanding of alliance sustainability as Europe faces growing expectations for autonomous security provision.[2] This study contributes to the ongoing debate on European responsibility within NATO and offers policy-relevant insights into the dynamics of burden-sharing in contemporary collective defense arrangements. Implications for future intra-European initiatives—such as the ESSI—are discussed in view of the observed burden-sharing patterns.

Our key contributions are threefold. First, we examine various weighted *Average Benefit Share* measure for European NATO that incorporates GDP, population, and novel proximity-based threat exposure, offering a more nuanced approximation of benefits.[3] Second, we introduce two novel proximity-based threat measures capturing spatial vulnerability to Russian aggression, allowing for a dynamic reassessment of threat exposure over time. Third, we update and extend the empirical analysis of European NATO and NATO burden-sharing from 1993 to 2022 using refined panel data. These innovations enable a reassessment of intra-European burden-sharing patterns, with particular relevance for European NATO and recent initiatives such as the ESSI. In doing so, we compare NATO and European NATO purely as different subsets of the same alliance, not to evaluate how Europe might compensate for the absence of US and Canadian contributions.

---

[2] These expectations are driven in part by repeated US signals to reduce its defense commitments to Europe and urging European allies to assume greater responsibility for their own security.

[3] Despite the use of unequal weights, we refer to this measure as the Average Benefit Share in line with prior literature. It is constructed as a weighted average of GDP share, population share, and proximity-based threat exposure to better reflect countries' heterogeneous benefit from collective defense.

3.2 | Related Literature

The issue of burden-sharing within military alliances has been extensively explored in economic literature, notably beginning with the seminal work by Olson and Zeckhauser (1966). By establishing the exploitation hypothesis, positing that alliances providing collective defense—which is assumed to be a public good—would suffer from underprovision by smaller or economically weaker members who free-ride on the efforts of wealthier or larger allies. In the NATO context, this hypothesis predicted that the US and other economically strong countries would disproportionately bear defense burdens.

Subsequent research refined this perspective, introducing the joint-product model, where defense expenditures produce both purely public benefits (such as deterrence) and impurely public or country-specific benefits (Sandler, 1977; Sandler and Forbes, 1980; Murdoch and Sandler, 1982). This shift allowed for a more nuanced analysis of NATO's evolving strategies, particularly the doctrine of flexible response adopted in 1967, which necessitated greater complementarity among allies' military capabilities (Sandler and Forbes, 1980). Sandler and Forbes argue that in the provision of collective defense, aligning allied contributions with received benefits is not merely an aspiration but an emergent expectation in cooperative settings. The study suggests that, over time the differences between actual defense burdens and those predicted on the basis of benefits should diminish. This convergence is attributed to increased awareness of common interests and an increase in the ratio of excludable benefits to the sum of excludable and non-excludable benefits. With an aggregate measure of allied benefits in hand, it is possible to compare actual defense shares with those derived from the three benefit proxies. There are numerous potential weighting methods for aggregating the various benefit measures, collectively referred to as the Average Benefit Share. Sandler and Forbes (1980) used three equally weighted determinants—a country's share of NATO's total population, its share of NATO's total GDP, and its share of NATO's total exposed border—to approximate benefit shares that align with relative defense burdens among NATO allies.

In later years, Khanna and Sandler (1996, 1997) proposed the hypothesis that NATO's defense expenditures are in concordance with the derived benefits and were unable to reject this hypothesis using a nonparametric Wilcoxon test for the following sample years: 1965, 1970, 1975, 1980, and 1990.[4] For the 1990s, this concordance is further corroborated by Sandler and Murdoch (2000), and from 1999 to 2002, this finding is additionally confirmed by Sandler and Shimizu (2014). However, the same study shows for the beginning of 2003 and extending through 2010, this concordance no longer holds; they reject the null hypothesis at the 0.05 level and conclude that defense burdens no longer match derived defense benefits.

The end of the Cold War significantly transformed NATO's strategic context, prompting scholars to reassess burden-sharing dynamics. The collapse of the Soviet Union eliminated NATO's primary threat, leading to new missions such as peacekeeping, humanitarian in-

---

[4] With one exception in 1985, at the height of the defense buildup under Reagan, NATO defense burdens were statistically inconsistent with the derived benefits.

terventions, and out-of-area operations (Shimizu and Sandler, 2003). These changes introduced greater heterogeneity in members' capabilities and priorities, complicating the burden-sharing calculus. In the following years, new dimensions of determinants have been added, such as those related to peacekeeping missions, for example, the number of soldiers stationed abroad. This has made burden sharing more precise and statistically robust in relation to defense expenditures (Bogers et al., 2022; Cooper and Stiles, 2021).

In their detailed examination of NATO from 1999 to 2010, Sandler and Shimizu (2014) highlighted a departure from previous concordance between defense burdens and derived benefits. They attributed this shift to several factors, including NATO's significant enlargement, increasing disparities in military technology investments (especially evident in R&D spending), and the growing importance of combating global terrorism post-9/11. Their empirical evidence, employing spearman rank correlation and Wilcoxon signed-rank tests, illustrated emerging patterns of exploitation, notably post-2004, and a weakening cohesion within NATO as a result of diverging security priorities and capacities. George and Sandler (2022) apply spatial econometric models to assess how defense spending by NATO allies in personnel, infrastructure, equipment, and maintenance categories exhibits strategic interdependence. They find the strongest free-riding in equipment investment—a capital-intensive domain prone to substitution—while infrastructure spending remains largely independent.[5]

In a similar vein, Feldman and Shipton (2024) focus on naval capabilities post-2014 and document a shift in spending patterns. They argue that US dominance in maritime security created a credible 'security umbrella', inducing other members to reallocate budgets away from naval forces. This finding supports burden-shifting hypotheses, whereby allies anticipate US coverage in strategic domains and underinvest accordingly.

While prior literature emphasized economic and strategic determinants of burden-sharing, Becker et al. (2024) introduce the role of political rhetoric—specifically, US presidential "naming and shaming."[6] Using a novel dataset of critical presidential statements, they assess the effect of public criticism on allied spending. Contrary to expectations, their panel regression analysis finds that rhetorical pressure is largely ineffective and may even backfire, correlating with decreased defense spending. This suggests that alliance cohesion may be undermined by aggressive political signaling, and that traditional variables like threat level and fiscal capacity remain better predictors of burden shifts.

Recognizing that defense spending alone provides an incomplete metric, recent studies have developed composite burden-sharing indices. Kim and Sandler (2024) propose a broadened measure that integrates foreign aid and peacekeeping expenditures, capturing a fuller spectrum of security contributions. Using spatial-lag panel models, they confirm classic

---

[5] According to George and Sandler (2022), equipment refers to movable, capital-intensive military assets (e.g. tanks, ships, aircraft), while infrastructure covers fixed installations (e.g. bases, airfields, logistics hubs), which are less prone to substitution or shared use. Notably, after the 2014 Wales Summit followed Russia's annexation of Crimea, allies collectively increased equipment spending, signaling responsiveness to geopolitical events (shocks).

[6] "Naming and shaming" refers to a rhetorical strategy in which political leaders publicly criticize or single out other actors, in this case, NATO allies, for not meeting expected defense contributions, with the intent of pressuring them into compliance.

free-rider patterns.

Kimball (2024) extend this logic further by analyzing NATO's Centers of Excellence (COEs)-shared institutional platforms for training and innovation—as club goods.[7] Their findings reveal that COE contributions do not align strictly with military budgets.

Unlike the Sandler and Shimizu (2014) approach, which compares defense burdens to derived benefit shares, the RAND report focuses on inputs and operational outputs, rather than measuring alliance benefits (Dreyer et al., 2024). The RAND report is the most comprehensive attempt to systematize NATO burden sharing, which introduces a multi-dimensional "Burdensharing Index". This index aggregates dozens of variables—including spending, personnel, and military output—into a composite score and burden-sharing ratio adjusted for economic capacity. The analysis finds that the commonly cited 2% GDP threshold obscures more than it reveals: some allies meeting this target contribute relatively little in operational output, while others below the threshold provide substantial non-financial capabilities.[8] RAND's findings support calls for a more nuanced, capability-focused assessment of allied contributions and offer policymakers a framework for differentiated burden-sharing.

Together, these recent studies represent a methodological and conceptual broadening of the burden-sharing literature, incorporating new metrics, refined econometric tools, and attention to institutional forms of alliance contribution. Building upon these insights, the current study further investigates burden-sharing among European NATO members from 1993 through 2022, a period marked by heightened geopolitical tensions, renewed threats from Russia, and shifting US commitments. By extending the empirical approach of Sandler and Shimizu (2014) with updated and refined datasets, this paper aims to clarify contemporary European NATO dynamics, offering critical insights into the alliance's ability to sustain and more balanced concordance between defense burdens and benefits.

The remainder of the paper is as follows. Section 3.3 describes the data sources, variable construction, and the methodology used to assess burden-sharing patterns. Section 3.4 tests the exploitation hypothesis using Spearman rank correlations and partial rank correlations. Section 3.5 examines the concordance between defense burdens and derived benefit shares using Wilcoxon signed-rank tests. Section 3.6 concludes and suggests directions for future research.

3.3 Data and Methods

Data on GDP (in current U.S. dollars), population (in number of inhabitants) and military expenditure are obtained from the World Bank (2024) Information on 'Exposed borders (EB)' and 'Exposed borders with Russia (EBR)' is drawn from the US Central Intelligence

---

[7] "Club goods", meaning they are institutional platforms where member countries share training, innovation, and expertise without full by every participant.

[8] Non-financial capabilities refer to contributions such as deployed personnel, logistics support, intelligence sharing, training efforts, and operational readiness—factors that enhance alliance capacity without necessarily increasing military spending.

Agency (2024). *EB* include only borders with non-NATO countries and coastlines; internal NATO borders are excluded. For instance, the Germany–France border is not considered, whereas the Poland–Belarus border is included, since Poland is a NATO member but Belarus is not.

EBR include only direct land borders that NATO countries share with the Russia (including the Kaliningrad exclave). For example, Estonia, Latvia, Lithuania, Norway, and Poland are considered to have exposed borders with Russia. Coastlines and borders with other non-NATO countries are excluded.

Because all rank correlations are calculated separately for each year, it is not necessary to adjust GDP or military expenditures (ME) for inflation. Relative measures, such as ME per GDP (ME/GDP), are constructed directly from these data (see Appendix Table B.2).

Distance categories (DC) are assigned based on geographic proximity to Russia. Countries sharing a direct land border with Russia receive a rank of 3; those separated from Russia by only one country receive a rank of 2; and all others receive a rank of 1. For example, Finland is assigned rank 3 as it shares a border with Russia; Sweden is assigned rank 2, with Finland in between; and France is assigned rank 1, given the multiple countries separating it from Russia. The Russian enclave of Kaliningrad is included in this measure, assigning Poland a rank of 3 as well. A full list of countries and their assigned categories can be found in Appendix Table B.3.

Methods

To evaluate burden-sharing within NATO and European NATO, we employ three complementary non-parametric statistical tests. First, we apply the Spearman rank correlation, which assesses whether countries with higher GDPs tend to allocate a greater share of GDP to defense. This test ranks all countries by GDP and by their ME burden (ME/GDP), and then calculates the correlation between these ranks. A positive correlation supports the exploitation hypothesis, indicating that wealthier members bear disproportionately high defense burdens.[9]

Second, we conduct partial Spearman rank correlation tests to control for confounding variables by excluding their effect on defense spending. These tests adjust the ranked relationship between GDP and ME/GDP by holding constant either GDP per capita (to account for levels of development) or both GDP per capita and the length of exposed borders (to capture geostrategic exposure). Formally, these are computed by first regressing the ranks of the variables of interest on the ranks of the control variables and then calculating the Spearman correlation between the resulting residual ranks.

Third, we apply two-sided Wilcoxon signed-rank tests to examine whether the distribution of defense burden shares aligns with the distribution of estimated benefit shares.[10]

---

[9] In this context, “disproportionately” means that a country’s defense burden (measured as the share of ME in GDP) increases more than proportionally with its GDP. That is, wealthier countries allocate a relatively larger share of their GDP to defense than poorer allies.

[10] The Wilcoxon signed-rank test evaluates whether the distribution of paired differences is symmetrically

Specifically, we compare each country's share of total alliance defense expenditures with four Average Benefit Shares (ABS), which combine GDP, population, and a threat-related proxy, and five Single Benefit Shares (SBS), which isolate each component individually. The SBSs are based on GDP, population, EB, EBR, and DC. These tests aim to determine whether significant asymmetries exist between a country's contributions to defense and its estimated benefits within the alliance. Specifically, we compare each country's share of total alliance defense expenditures with four ABSs and five SBSs. These tests aim to determine whether significant asymmetries exist between a country's contributions to defense and its estimated benefits within the alliance. For each country-year observation, we compute the difference between the country's defense burden (its share of European NATO total ME) and its benefit share (proxied by GDP, population, and three alternative threat measures). The Wilcoxon test ranks the absolute values of these differences, assigns signs according to the direction of deviation, and sums the signed ranks. The resulting test statistic indicates whether the median difference between burden and benefit shares is significantly different from zero. A rejection of the null hypothesis implies lost concordance between defense burdens and benefits, pointing to potential free-riding behavior (see illustrative example in Appendix Table B.1).

3.4 | Ability to Pay and Burden Sharing

This section introduces the empirical tests used to assess whether defense burdens are distributed in proportion to members' economic capacity. We test the exploitation hypothesis, first for the NATO members and then for European NATO members.

3.4.1 | NATO

Originally invented by Olson and Zeckhauser (1966), the ratio of ME to GDP (ME/GDP) has become the standard measure of ability to pay and burden sharing. Building on the approach of Sandler and Shimizu (2014), who examined data from 1999-2010, we extend the test of the exploitation hypothesis for the period 1993-2022—namely, whether wealthier allies bear disproportionate defense burdens—by employing a Spearman rank correlation between ME/GDP and GDP.

> H_1 : Within the NATO alliance, there is a positive association between allies' GDP and their share of GDP devoted to MEs.
>
> H_0 : There is no association between these two variables.

---

centered around zero. Unlike a mean-based test (e.g., paired *t*-test), which focuses on average deviation, the Wilcoxon signed-rank tests captures distributional asymmetries around the median. In the context of burden-sharing, it reveals whether countries systematically over- or under-contribute relative to their estimated benefit share. A significant result indicates a shift in the median of the distribution, suggesting collective imbalance—such as widespread free-riding or overcontribution—rather than random fluctuation around the median.

A statistically significant positive rank correlation, leading to rejection of the null hypothesis, indicates that higher-income allies contribute a greater share of their GDP to defense.[11] The second and third tests are partial rank correlation tests that control for factors that may influence countries' defense spending. The second test examines the correlation between GDP and ME/GDP while holding GDP per capita (GDP/POP) constant. This is particularly important because countries with greater economic prosperity have more to protect and are thus more likely to allocate more for defense. The third test examines correlation between GDP and ME/GDP while holding GDP per capita (GDP/POP) and exposed borders constant.

For the first test, we confirmed the results of Sandler and Shimizu (2014) that the null hypothesis cannot be rejected in the period from 1999 to 2010, and therefore found no evidence of exploitation of the rich by the poor (see Table 3.1). However, the null hypothesis was rejected in 2011, 2012, 2014, and 2015 at the 0.1 significance level, and in 2012 at the 0.05 level, indicating exploitation during the period 2011–2015—especially as the correlation coefficient steadily increased between 2007 and 2012. We did not find strong evidence of continued exploitation after 2015, as the correlation coefficients were no longer statistically significant in the following years.

In the second test, with GDP/POP held constant, we cannot reject the null hypothesis from 1999 to 2003, but we found evidence of exploitation at the 0.1 significance level or better in 2004–2017 (except for 2007), and again in 2020. This confirms the findings of Sandler and Shimizu (2014) for 2004, 2005, 2006, and 2010, but additionally allows rejection of the null hypothesis in 2008 and 2009.

In the third test, with GDP/POP and EBs held constant, the null hypothesis cannot be rejected in any year, consistent with the results of Sandler and Shimizu (2014).

Overall, we confirmed the conclusion of Sandler and Shimizu (2014) by showing that NATO increasingly relied on fewer rich allies during the period 1999–2010. We extended this finding to the years 2011-2015 and 2017. After 2017, however, we find only limited evidence for the exploitation hypothesis, notably in 2020 by holding GDP/POP constant.

These results suggest that defense expenditures and GDP must be shared more proportionally. This is particularly relevant given that countries with low GDP—such as Albania, Bulgaria, North Macedonia, and Poland—increased their defense contributions over this period more than higher-income countries such as the US, Canada, or the UK (see in Appendix Table B.2. This shift is especially noteworthy in light of Donald Trump's rise to power in 2017 and the pressure he exerted on European allies to increase their defense spending.

---

[11] The Spearman test is particularly suited to this context, as it is non-parametric, robust to outliers, and appropriate for samples combining very large and small allies. This makes the test less sensitive to outliers or small errors because ranks, instead of values, are used. That is particularly appropriate when comparing countries of different sizes—such as the US and Albania.

Table 3.1: Spearman rank correlation between defense burden (ME/GDP) and GDP in NATO

	ρ_{12}^{a}	$\rho_{12,3}^{b}$	$\rho_{12,34}^{c}$
1993	0.23 (0.40)	0.25 (0.38)	0.13 (0.68)
1994	0.22 (0.43)	0.26 (0.38)	0.12 (0.68)
1995	0.11 (0.70)	0.15 (0.61)	0.05 (0.86)
1996	0.15 (0.58)	0.19 (0.51)	0.10 (0.74)
1997	0.21 (0.44)	0.25 (0.40)	0.13 (0.67)
1998	0.22 (0.42)	0.24 (0.42)	0.09 (0.77)
1999	0.20 (0.43)	0.27 (0.29)	0.05 (0.86)
2000	0.22 (0.37)	0.35 (0.17)	0.13 (0.64)
2001	0.18 (0.47)	0.30 (0.24)	0.07 (0.81)
2002	0.15 (0.56)	0.22 (0.39)	− 0.05 (0.86)
2003	0.20 (0.42)	0.27 (0.29)	0.03 (0.90)
2004	0.19 (0.37)	0.42** (0.04)	0.17 (0.44)
2005	0.14 (0.51)	0.41** (0.04)	0.20 (0.36)
2006	0.17 (0.43)	0.39* (0.06)	0.19 (0.40)
2007	0.13 (0.54)	0.32 (0.12)	0.06 (0.80)
2008	0.18 (0.39)	0.35* (0.09)	0.10 (0.66)
2009	0.23 (0.25)	0.34* (0.09)	0.06 (0.77)
2010	0.28 (0.16)	0.39* (0.05)	0.13 (0.55)
2011	0.35* (0.07)	0.47** (0.02)	0.19 (0.36)
2012	0.39** (0.05)	0.49** (0.01)	0.22 (0.30)
2013	0.32 (0.10)	0.48** (0.01)	0.21 (0.31)
2014	0.33* (0.10)	0.46** (0.02)	0.16 (0.44)
2015	0.34* (0.09)	0.47** (0.01)	0.17 (0.41)
2016	0.22 (0.26)	0.35* (0.08)	− 0.06 (0.79)
2017	0.17 (0.38)	0.34* (0.07)	− 0.02 (0.92)
2018	0.11 (0.59)	0.31 (0.12)	− 0.08 (0.69)
2019	− 0.02 (0.94)	0.22 (0.27)	− 0.09 (0.65)
2020	0.16 (0.42)	0.32* (0.09)	0.00 (0.98)
2021	0.06 (0.75)	0.28 (0.16)	0.00 (0.98)
2022	− 0.09 (0.65)	0.07 (0.72)	− 0.15 (0.46)

(*Notes.* This table reports Spearman rank correlations testing the association between countries' GDP and their relative defense burden, measured as ME/GDP, within NATO from 1993 to 2022. The test evaluates: whether wealthier allies contribute a greater share of their GDP to defense. A statistically significant positive rank correlation between ME/GDP and GDP suggests that wealthier countries contribute a larger share of their GDP to defense, consistent with the exploitation hypothesis and the free-riding behavior of lower-income allies. Numbers in parentheses are prob-values, indicating the probability of a type I error when testing the null hypothesis of no association between ME/GDP and GDP ranks.

*** significant at .01 level; ** significant at .05 level; and * significant at .10 level.

Variables: 1 = ME/GDP; 2 = GDP; 3 = GDP/POP; 4 = exposed borders.

[a] Simple rank correlation coefficient.

[b] Partial rank correlation coefficient with GDP/POP held constant.

[c] Partial rank correlation with GDP/POP and exposed borders held constant.)

3.4.2 European NATO

We replicate the same testing in Section 3.4.1 to the European NATO to see if the exploitation hypothesis holds in Europe, especially in the context of the US announcement that it will withdraw from Europe, leaving the European allies to bear a larger share of their defense burden.[12]

For the first simple Spearman rank correlation test between ME/GDP and GDP, we can only reject the null hypothesis in 2012 at the 0.1 significance level (see Table 3.2). However, in general, we find rather low values for the correlation coefficient over the whole period from 1993 to 2022. Therefore, we do not find any evidence of persistent exploitation.

In the second test, holding GDP/POP constant, we identify two phases of exploitation, the first from 2004 to 2006 and the second from 2010 to 2015, where we can reject the null hypothesis at the 0.1 significance level or better. This is in line with the findings of Section 3.4.1, although the second exploitation phase is shorter as we find no evidence of exploitation in 2008, 2009 and 2016, 2017.

Consistent with Section 3.4.1, we cannot reject the null hypothesis at any point in the third test with GDP/POP and exposed borders held constant. Indeed, the correlation coefficients are low throughout the period.

Combining these results, we can observe some disproportionality in defense burden-sharing among European allies, particularly during the period from 2004 to 2015, when GDP/POP is held constant. However, these imbalances appear to be less severe and less persistent than for NATO as a whole. This is because the US, with its disproportionately defense spending, and Canada, with its disproportionately low defense spending, are not included.

---

[12] Although the Spearman rank correlation is robust to outliers in the magnitude of values, the removal of large members such as the United States and Canada affects the relative ranking of the remaining countries. Since Spearman's ρ is based on the correlation between ranks, excluding high-GDP countries like the US alters the rank structure and can meaningfully change the correlation results. Therefore, differences between the NATO and European NATO tests are not only expected but also informative.

Table 3.2: Spearman Rank correlation between defense burden (ME/GDP) and GDP in European NATO

	ρ^a_{12}	$\rho^b_{12,3}$	$\rho^c_{12,34}$
1993	0.08 (0.79)	0.07 (0.83)	0.05 (0.87)
1994	0.06 (0.85)	0.08 (0.79)	0.06 (0.87)
1995	− 0.01 (0.99)	0.01 (0.98)	− 0.04 (0.90)
1996	0.02 (0.96)	0.03 (0.94)	− 0.03 (0.94)
1997	0.13 (0.67)	0.15 (0.64)	0.14 (0.69)
1998	0.16 (0.60)	0.15 (0.65)	0.08 (0.82)
1999	0.18 (0.51)	0.26 (0.34)	0.02 (0.95)
2000	0.21 (0.44)	0.32 (0.24)	0.08 (0.78)
2001	0.15 (0.59)	0.26 (0.35)	− 0.01 (0.97)
2002	0.06 (0.81)	0.14 (0.61)	− 0.28 (0.34)
2003	0.11 (0.70)	0.20 (0.47)	− 0.15 (0.60)
2004	0.15 (0.50)	0.45** (0.04)	0.16 (0.49)
2005	0.10 (0.66)	0.42* (0.05)	0.21 (0.37)
2006	0.13 (0.56)	0.38* (0.08)	0.16 (0.49)
2007	0.06 (0.78)	0.28 (0.20)	− 0.01 (0.97)
2008	0.10 (0.63)	0.30 (0.17)	0.03 (0.88)
2009	0.17 (0.42)	0.30 (0.16)	0.02 (0.93)
2010	0.23 (0.27)	0.35* (0.10)	0.07 (0.75)
2011	0.31 (0.13)	0.44** (0.03)	0.16 (0.47)
2012	0.35* (0.08)	0.46** (0.02)	0.16 (0.46)
2013	0.29 (0.17)	0.46** (0.02)	0.17 (0.45)
2014	0.27 (0.20)	0.43** (0.04)	0.12 (0.57)
2015	0.28 (0.18)	0.45** (0.03)	0.16 (0.47)
2016	0.15 (0.48)	0.30 (0.16)	− 0.11 (0.61)
2017	0.08 (0.68)	0.30 (0.14)	− 0.05 (0.82)
2018	0.02 (0.94)	0.25 (0.23)	− 0.13 (0.54)
2019	− 0.11 (0.60)	0.16 (0.43)	− 0.15 (0.48)
2020	0.09 (0.65)	0.28 (0.16)	− 0.04 (0.86)
2021	0.00 (0.98)	0.23 (0.25)	− 0.07 (0.75)
2022	− 0.17 (0.41)	0.00 (1.00)	− 0.22 (0.28)

(*Notes.* This table reports Spearman rank correlations testing the association between countries' GDP and their relative defense burden, measured as ME/GDP, within European NATO from 1993 to 2022. The test evaluates: whether wealthier allies contribute a greater share of their GDP to defense. A statistically significant positive rank correlation between ME/GDP and GDP suggests that wealthier countries contribute a larger share of their GDP to defense, consistent with the exploitation hypothesis and the free-riding behavior of lower-income allies. Numbers in parentheses are prob-values, indicating the probability of a type I error when testing the null hypothesis of no association between ME/GDP and GDP ranks.
*** significant at .01 level; ** significant at .05 level; and * significant at .10 level.
Variables: 1 = ME/GDP; 2 = GDP; 3 = GDP/POP; 4 = exposed borders.
[a] Simple rank correlation coefficient.
[b] Partial rank correlation coefficient with GDP/POP held constant.
[c] Partial rank correlation with GDP/POP and exposed borders held constant.)

3.5 | The Concordance between Defense Burdens and Benefit Shares

This section examines whether the defense burden aligns with the benefits for European NATO members. To support this analysis, Appendix Section B.5 provides detailed input data and results for European NATO members. For comparison, the corresponding analysis for all NATO members is included in Appendix Section B.6. We compare each country's defense burden with a series of average benefit share measures. The analysis is based on the assumption that, in the long term, the defense burden will align with the benefits; significant and persistent deviations may indicate free-riding behavior. To test for distributional concordance between burdens and benefits, we employ non-parametric Wilcoxon signed-rank tests across average benefit share measures. Each benefit share integrates economic capacity, demographic weight, and threat exposure, with four variations capturing different proxies for geopolitical vulnerability. We apply these tests first to European NATO members and then, for comparison, to the whole NATO alliance.

3.5.1 | European NATO

Following Sandler and Shimizu (2014), we investigate the relationship between an ally's defense burden and its average benefit share, focusing on European NATO. The defense burden is measured by a country's share of the total defense expenditures of all European NATO members (excluding Iceland).[13]

Since countries' preferences are unknown, including how they weigh the benefits of protecting the economy, the population, or countering an external threat, we construct four ABS measures. Each ABS is based on an equal weighting of three proxies: GDP share, population share, and a threat-related factor. The third proxy captures threat (e.g., representing the threat posed by Russia to the allies due to its military aggression against Ukraine) and various across the different ABSs.[14] These measures are central to the analysis and are defined as follows:

- ABS 1: Includes GDP share, population share, and an ally's share of total EB (include only borders with non-NATO countries and coastlines; internal NATO borders are excluded) following Sandler and Forbes (1980).
- ABS 2: Replaces the exposed border proxy with the share of EBR, reflecting the idea that these borders are the most vulnerable and therefore require greater protection.
- ABS 3: Replaces the EB measure with a proximity-based threat in which countries are assigned DC that represent the relative threat posed to a country based on its proximity to Russia. In this case, a country's assigned rank is divided by the sum of the ranks across all allies.

---

[13] Note that Iceland is not included since it does not have defense expenditures. This follows standard practice in the existing literature.

[14] ABSs denotes the plural form *Average Benefit Shares*, extending the acronym ABS (Average Benefit Share) with an additional "s".

- ABS 4: Combines the three threat components from ABS 1–3 by averaging them equally alongside GDP and population shares.

Alternative weightings are examined as part of the robustness checks in Appendix Section B.7

To investigate the correspondence between defense burdens and the average benefit share, we follow Sandler and Shimizu (2014) and use a two-sided Wilcoxon signed-rank test. This non-parametric test compares two dependent samples by ranking the absolute differences between paired observations and summing the ranks separately for positive and negative differences. The test statistic R corresponds to the smaller of the two rank sums and is used to evaluate whether the median difference is significantly different from zero.[15] When we use the term concordance, we mean that no statistically significant loss of concordance has been detected.

H_1 : The distributions of defense burdens and average benefit shares are different.

H_0 : The distributions of defense burdens and average benefit share are the same.

A small Wilcoxon test statistic suggests that the null hypothesis can be rejected, implying a lost concordance between the country's defense burdens and average benefit share.

Table 3.3 displays the test statistic for the H_0 "The distributions of defense burdens and average benefit share are the same.", for the four average benefit share alternatives for the period 1993-2022. Note that the sample size increases with NATO expansions. For the ABS 1 (exposed borders), the null hypothesis is rejected at the significance level of 0.1 or better in 2005, from 2014 to 2017, and in 2019. These results indicate intermittent divergence between defense burden and benefit shares in certain years, particularly in the last decade. While this does not imply a persistent mismatch, it suggests that alignment has been increasingly strained in recent years. This may also indicate that free-riding behavior has occurred occasionally, especially in the last decade. Although these patterns point to a possible trend toward greater free-riding, there is still no evidence of sustained or systematic free-riding behavior over the whole period.

No rejection of the null hypothesis is found when ABS 2 (borders with Russia) is used, implying that this proxy maintains distributional concordance between defense burdens and benefit shares across the entire period.

In contrast, for ABS 3 (distance categories), the null hypothesis is rejected at conventional levels in almost every year from 2004 to 2021, except for 2008. This consistent rejection points to a prolonged period during which defense burdens and derived benefits no longer align, particularly after NATO's eastern enlargement and amid heightened geopolitical

---

[15] Although the Wilcoxon signed-rank test formally tests whether the median difference between paired observations is zero, it is often interpreted in practice–especially in the burden-sharing literature–as a test of distributional concordance between matched samples. Statistically, the null hypothesis states: The median difference between the defense burdens and the average benefit share is zero.

tensions. Such sustained mismatch may signal that defense burdens no longer match with this average benefit share, or increased incentives for free-riding within the alliance. The single benefit share analysis will later will provide greater clarity on this issue.

The three alternatives for the average benefits share, therefore, lead to different conclusions. Looking at the three alternatives, it becomes clear that they favor or disfavor different countries. The exposed borders alternative poses a high threat to countries bordering the allied territory. Countries with a fragmented border or coastline are particularly favored. For example, countries like Greece, which have many islands, receive a high average share of benefits, even though the islands are in waters shared with other NATO members. Countries that are not on the border of allied territory or those that are large tend to be disadvantaged. This average benefit share alternative also does not take into account a country's location and therefore does not take into account the threat posed by Russia's invasion of Ukraine. The exposed border with Russia alternative favors countries with direct borders with Russia, regardless of their location, and does not take coastlines into account. Thus, it assigns the same threat level of zero to Spain and Romania, even though Romania is much closer to Russia and was part of the Warsaw Pact. However, the Baltic states receive a relatively high average benefit share because they all share a border with Russia. The alternative with distance categories takes into account the relative location to Russia and assigns a basic threat to all countries, as there is no rank zero. This favors small countries and those close to Russia. For example, Poland and the Baltic states receive the same benefit from the threat factor because they all share a border with Russia, even though Poland is much larger than the Baltic states. There might be time-dependent relevance differences between the proxies as the threat posed by Russia was less severe in the post-Cold War era after 1991, compared to the period after the annexation of Crimea in 2014 or after the invasion of Ukraine in 2022. Especially in the last decade, the threat posed by Russia and the respective benefit share proxies became more relevant, while the more universal exposed border threat measure was more relevant in the period before 2014.

However, since all three average benefit share alternatives include reasonable benefits from defense spending, and in order to counter the respective imbalances in benefit shares, we have combined the different threat measures into one to get a broader view of the benefits from defense over the whole period. With this combined measure, ABS 4, does not exhibit statistical concordance with defense burdens across all years, this does not disqualify its relevance. On the contrary, the rejection of the null hypothesis in periods such as 2005 and 2013–2021 highlights a growing misalignment between defense burden and benefits. As the R statistic shows an increasing trend over the period from 1997 to 2022, we discern an increased trend toward free-riding in the European NATO, culminating in the period 2013-2021, where only the UK, France, Germany and the Netherlands overcontributed according to this average benefit share measure. This changed in 2022, when Belgium, Greece, and Spain also became overcontributors. Thus, rather than undermining its value, the statistical rejection of ABS 4 underscores its strength as a composite diagnostic indicator for identifying structural imbalances in European NATO burden-sharing.

Table 3.3: Wilcoxon signed-rank correlation of ME/European NATO ME and alternative Average Benefit Shares

		Average Benefit Share 1	Average Benefit Share 2	Average Benefit Share 3	Average Benefit Share 4
Year	Size	R (p)	R (p)	R (p)	R (p)
1993	13	39 (0.68)	23 (0.13)	29 (0.27)	36 (0.54)
1994	13	40 (0.74)	25 (0.17)	28 (0.24)	37 (0.59)
1995	13	39 (0.68)	25 (0.17)	31 (0.34)	36 (0.54)
1996	13	40 (0.74)	24 (0.15)	30 (0.31)	40 (0.74)
1997	13	41 (0.79)	22 (0.11)	29 (0.27)	41 (0.79)
1998	13	39 (0.68)	22 (0.11)	29 (0.27)	41 (0.79)
1999	16	55 (0.53)	44 (0.23)	48 (0.32)	60 (0.71)
2000	16	55 (0.53)	42 (0.19)	47 (0.30)	59 (0.67)
2001	16	56 (0.56)	49 (0.35)	47 (0.30)	57 (0.60)
2002	16	54 (0.50)	47 (0.30)	44 (0.23)	56 (0.56)
2003	16	56 (0.56)	48 (0.32)	44 (0.23)	55 (0.53)
2004	23	92 (0.17)	134 (0.92)	80* (0.08)	89 (0.14)
2005	23	80* (0.08)	137 (0.99)	74* (0.05)	81* (0.09)
2006	23	86 (0.12)	136 (0.96)	78* (0.07)	91 (0.16)
2007	23	88 (0.13)	135 (0.94)	74* (0.05)	91 (0.16)
2008	23	96 (0.21)	137 (0.99)	86 (0.12)	97 (0.22)
2009	25	103 (0.11)	160 (0.96)	100* (0.10)	111 (0.17)
2010	25	103 (0.11)	160 (0.96)	95* (0.07)	103 (0.11)
2011	25	102 (0.11)	158 (0.92)	94* (0.07)	104 (0.12)
2012	25	102 (0.11)	158 (0.92)	90* (0.05)	104 (0.12)
2013	25	102 (0.11)	162 (1.00)	94* (0.07)	97* (0.08)
2014	25	90* (0.05)	153 (0.81)	88** (0.05)	95* (0.07)
2015	25	95* (0.07)	156 (0.87)	84** (0.03)	86** (0.04)
2016	25	95* (0.07)	159 (0.94)	92* (0.06)	97* (0.08)
2017	26	108* (0.09)	174 (0.98)	101* (0.06)	103* (0.07)
2018	26	116 (0.14)	172 (0.94)	101* (0.06)	108* (0.09)
2019	26	108* (0.09)	149 (0.52)	97** (0.05)	109* (0.09)
2020	27	133 (0.19)	175 (0.75)	108* (0.05)	115* (0.08)
2021	27	139 (0.24)	173 (0.71)	116* (0.08)	114* (0.07)
2022	27	147 (0.32)	162 (0.53)	119* (0.10)	122 (0.11)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. The construction of Average Benefit Shares are explained in the first paragraph of 3.5.1. In parentheses are prob-values, indicating the probability of a type I error. ***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

Table 3.4 shows the test statistics of a Wilcoxon signed-rank test for the single benefit shares with ME/European NATO. These results provide insight into which proxies contribute to the observed concordance—or lack thereof—between defense burden and benefit shares. For GDP, population, exposed border and distance category, there is a concordance with the defense burden sharing over the whole period, except for GDP in 2009 and 2010, where the null hypothesis can be rejected at a significance level of 0.1. This shows that these factors are drivers of defense burden sharing in Europe. For the exposed border with Russia, the null hypothesis can be rejected from 1993 to 2003 and from 2020 to 2022 at a significance level of 0.1 or better. This can be explained by the fact that in 1999, Norway was the only NATO member with a direct border with Russia, resulting to a disproportionate average benefit share for Norway. Poland joined NATO in 1999, followed by the Baltic states in 2004, resulting in a more evenly distributed benefit share. Therefore, we do not want to put too much emphasis on the Wilcoxon test of this average benefit share in the period prior to 2004. We conclude that all of the proxies considered are drivers of burden sharing in European NATO. As shown in Table 3.4 our findings are robust across the single benefit shares, provided that none of them is given too much weighting. We are unable to reject the null hypothesis for any of the proxies except GDP in 2009 and 2010 and the exposed border with Russia from 2020 to 2022. Notably, the exposed border with Russia yields consistently low R statistics, suggesting a potential misalignment that does not reach conventional levels of statistical significance.[16]

Thus, no specific benefit proxy can be pinpointed as responsible for the lost concordance between average benefit and burden shares, especially in the period from 2013 to 2021. Therefore, the lost concordance must result from the cumulative distribution shifts of the combined benefit proxies. However, we are able to reject the null hypothesis for the EBR during the period from 2020 to 2022. In addition, we observe an overall low and continuously decreasing R statistic after 2008, partly due to NATO expansions. The strongest concordance with the defense burdens is found for ABS 2, which incorporates this benefit proxy. Therefore, we conclude that the EBR offsets asymmetries arising from GDP and population differences. To explore this further, an investigation of the years after 2022 would be particularly interesting, as countries sharing a direct border with Russia showed strong bilateral support for Ukraine relative to their GDP (Ethan Ilzetzki, 2025).

The Figure 3.1 shows the defense burdens and ABS 4—which combines GDP, population, and three different threat measures (exposed borders, exposed borders with Russia, and distance category)—for all European NATO members from 1993 to 2022 (see Table B.4 in the Appendix for details). Figure B.1 in the Appendix illustrates ABS 2, which combines GDP, population, and EBR. The data for the first three ABs are listed in the Appendix in Table B.6.

For instance, in the ABS 4 method, Belgium bore 2.26% of the total European defense burdens in 1993 and received an average benefit share of 2.47%. This makes Belgium an

---

[16] The temporary rejection of the null for GDP in 2009 and 2010 coincides with the fiscal aftermath of the 2008 global financial crisis, during which many NATO members reduced defense budgets as part of broader consolidation efforts (World Bank, 2024).

Table 3.4: Wilcoxon signed-rank correlation of ME/European NATO ME and single benefit shares

		GDP	POP	EB	EBR	DC
Year	Size	R (p)	R (p)	R (p)	R (p)	R (p)
1993	13	39 (0.68)	43 (0.89)	40 (0.74)	13** (0.02)	42 (0.84)
1994	13	40 (0.74)	44 (0.95)	40 (0.74)	13** (0.02)	42 (0.84)
1995	13	43 (0.89)	43 (0.89)	41 (0.79)	13** (0.02)	41 (0.79)
1996	13	42 (0.84)	45 (1.00)	40 (0.74)	13** (0.02)	42 (0.84)
1997	13	41 (0.79)	40 (0.74)	40 (0.74)	13** (0.02)	43 (0.89)
1998	13	43 (0.89)	42 (0.84)	40 (0.74)	13** (0.02)	42 (0.84)
1999	16	56 (0.56)	62 (0.78)	63 (0.82)	31* (0.06)	60 (0.71)
2000	16	54 (0.50)	57 (0.60)	60 (0.71)	31* (0.06)	59 (0.67)
2001	16	56 (0.56)	58 (0.63)	58 (0.63)	31* (0.06)	58 (0.63)
2002	16	59 (0.67)	57 (0.60)	60 (0.71)	31* (0.06)	57 (0.60)
2003	16	58 (0.63)	58 (0.63)	61 (0.74)	31* (0.06)	59 (0.67)
2004	23	107 (0.36)	103 (0.30)	128 (0.78)	96 (0.21)	102 (0.29)
2005	23	111 (0.43)	104 (0.31)	138 (1.00)	97 (0.22)	105 (0.33)
2006	23	102 (0.29)	99 (0.25)	134 (0.92)	96 (0.21)	106 (0.34)
2007	23	98 (0.23)	96 (0.21)	135 (0.94)	96 (0.21)	107 (0.36)
2008	23	95 (0.20)	108 (0.38)	136 (0.96)	98 (0.23)	109 (0.39)
2009	25	98* (0.09)	127 (0.35)	149 (0.73)	108 (0.15)	121 (0.28)
2010	25	98* (0.09)	122 (0.29)	159 (0.94)	108 (0.15)	121 (0.28)
2011	25	104 (0.12)	126 (0.34)	157 (0.89)	108 (0.15)	118 (0.24)
2012	25	105 (0.13)	112 (0.18)	155 (0.85)	108 (0.15)	119 (0.25)
2013	25	108 (0.15)	111 (0.17)	156 (0.87)	108 (0.15)	115 (0.21)
2014	25	107 (0.14)	108 (0.15)	152 (0.79)	108 (0.15)	115 (0.21)
2015	25	111 (0.17)	103 (0.11)	153 (0.81)	108 (0.15)	113 (0.19)
2016	25	126 (0.34)	112 (0.18)	157 (0.89)	108 (0.15)	119 (0.25)
2017	26	149 (0.52)	119 (0.16)	166 (0.82)	113 (0.12)	127 (0.23)
2018	26	150 (0.53)	127 (0.23)	172 (0.94)	113 (0.12)	128 (0.24)
2019	26	170 (0.90)	126 (0.22)	169 (0.88)	113 (0.12)	130 (0.26)
2020	27	186 (0.95)	147 (0.32)	186 (0.95)	119* (0.10)	128 (0.15)
2021	27	179 (0.82)	159 (0.48)	188 (0.99)	118* (0.09)	130 (0.16)
2022	27	170 (0.66)	173 (0.71)	186 (0.95)	118* (0.09)	130 (0.16)

(*Notes.* Numbers in parentheses are prob-values, indicating the probability of a type I error when testing the null hypothesis. ***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004-2008; are 89 at .05 level and 68 at .01 level for 2009-2016; are 98 at .05 level and 75 at .01 level for 2017-2019; are 107 at .05 level and 83 at .01 level for 2020-2022. Iceland is excluded for all years.)

undercontributor according to this average benefit share measure. The biggest contributors are the United Kingdom, Germany and France in all years considered. They collectively contributed 65.59% to the total European NATO defense expenditures in 1993, 59.33% in 2003, 56.84% in 2013 and 54.14% in 2022. By taking into account the NATO expansion in 1999 (Poland, Czechia, Hungary), 2004 (Bulgaria, Estonia, Latvia, Lithuania, Romania, Slovakia, Slovenia), 2009 (Albania, Croatia), 2017 (Montenegro) and 2020 (North Macedonia) we still conclude that the overall share of the biggest three contributors decreased successively since the newcomers collectively contributed 11.08% of the total European NATO defense expenditures in 2022. Germany lowered its defense expenditure share significantly in the 90s and then kept it at a constantly low level with a slight upwards trend. Contrarily, the United Kingdom raised its share in the 90s, kept it constant at around 25% and then successively lowered its share from 2007 to 2017 and then kept it constant at around 20%. France lowered its share gradually over the period from around 22% to 17%. For all three countries, the ABS remains almost constant and only decreases significantly in 1999 and 2004 due to NATO expansions. The expansions in 2009, 2017 and 2020 are too small to have a strong effect on the ABS, as only a few relatively small countries join NATO. The collective ABS of the United Kingdom, Germany and France decreases from 41.58% in 1993 to 32.76% in 2022. This still makes the largest countries overcontributors, but they appear to have offset the declining average benefit with a declining overall defence burden share. Overall, there were 4 out of 9 overcontributors in 1993 (France, Germany, Netherlands, United Kingdom) and 9 out of 33 in 2022 (Belgium, France, Germany, Greece, Italy, Netherlands, Spain, United Kingdom). This makes most of the largest European countries overcontributors while most of the smaller nations are undercontributors, suggesting that Europe suffers from free-riding and the exploitation hypothesis of Olson and Zeckhauser (1966). However, this does not seem as clear-cut as the free-riding problem in NATO as a whole, with the large overcontribution of the US.

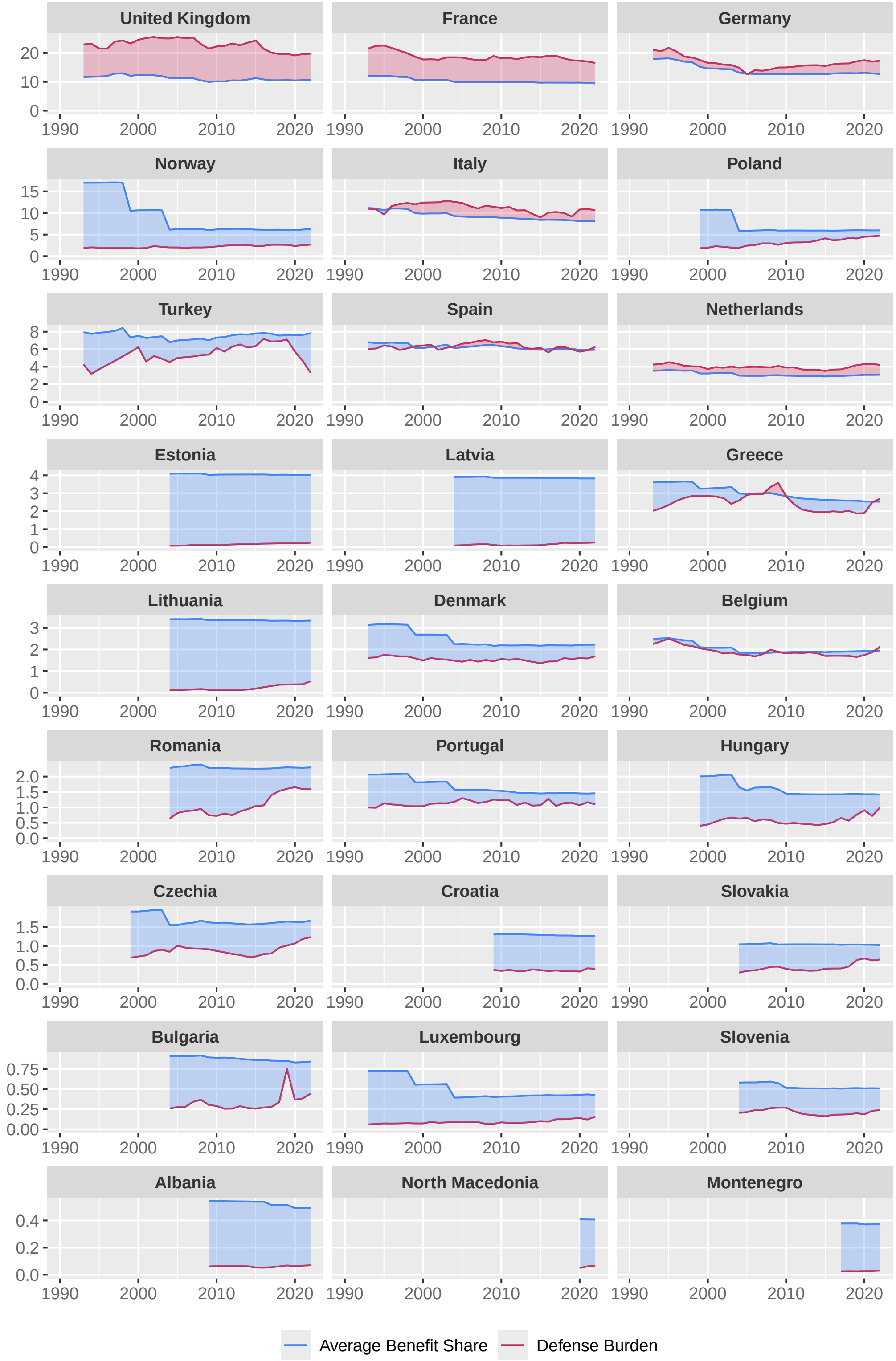


Figure 3.1: The figure displays evolution of Defense Burdens (as a percentage share) for 27 European NATO members, alongside their derived Average Benefit Share 4. Each row uses a different vertical scale. The horizontal axis represents the years 1993 to 2022.

3.5.2 | Comparison to NATO

The lost concordance identified for European NATO—apart from the concordant results under ABS 2—appears modest when compared to the divergence observed for the whole NATO alliance. As shown in Table B.8 in the Appendix, the Wilcoxon signed-rank test strongly rejects the null hypothesis of distributional equivalence at the 0.01 level from 2004 onward. In this contemplation, the USA is the only overcontributor from 2004 onward, as displayed in the Appendix in Table B.10. However, with the announcements of the US to withdraw from Europe and in particular the reelection of Donald Trump in 2024, Europe is expected to be no longer able to take advantage of US defense spending making burden sharing among European allies relevant especially with the potential necessity of an increase of the defense expenditure in Europe.

(a) ABS 4 and Defense Burden share of the three largest European NATO members by GDP (France, Germany, and the United Kingdom) within European NATO

(b) ABS 4 and Defense Burden share of the US within NATO

Figure 3.2: Comparison of ABS 4 and corresponding Defense Burden shares for the largest GDP contributors in European NATO (France, Germany, and the United Kingdom) and in the NATO (the US).

Figure 3.2a shows the ABS 4 and defense burden share of the three largest European NATO members (France, Germany, UK) within European NATO. It can clearly be seen that these countries are overcontributing, as the benefit is lower than the defense burden in all years considered. Figure 3.2b shows the ABS 4 and the defense burden share of the USA within the whole NATO. It is clear that the US is overcontributing. This symmetry implies that France, Germany, and the United Kingdom collectively bear a burden within European NATO that parallels the US burden within the broader NATO alliance, both in terms of defense burdens and benefit shares. This seems to contradict the trend indicated by the Wilcoxon signed-rank tests, which suggest a possible pattern of free-riding within the entire NATO, but only weak evidence of such behavior during certain periods within European NATO. This apparent discrepancy may stem from the fact that overcontributions in European NATO are distributed across three sovereign countries. Although their combined population approaches that of the US (nearly 65%) and their joint GDP reaches roughly

40% of the US level, the statistical signal of overcontribution is diluted when these efforts are spread across multiple states (World Bank, 2024). As a result, the Wilcoxon tests detect weaker deviations from benefit–burden alignment in European NATO, even though the aggregate pattern closely resembles that of the US within the broader alliance.

3.6 | Concluding Remarks

In this paper, we examine various methods for estimating the average benefit shares within alliances from European NATO and NATO. We identify a lost concordance for the period 1993 to 2022, along with suggested methods of average benefit sharing for NATO. However, we identify a novel ABS 2—based on exposed borders with Russia—that maintains statistical concordance with defense burdens in European NATO throughout the observation period. Upon examining the drivers of this concordance, we find that all single benefit shares are consistent with proportional burden sharing. An exception are the benefit shares of countries with exposed borders with Russia in certain years and GDP during 2009-2010. This suggests that these shares broadly capture the underlying logic of defense contribution, while deviations appear to result from structural factors such as alliance enlargement or external shocks like the global financial crisis. Building on this, we construct a composite ABS 4 that integrates the previously defined proxies—ABSs 1, 2, and 3. This combined measure fails to exhibit statistical concordance with defense burdens, when tested using the Wilcoxon signed-rank test. While this outcome points to potential free-riding incentives within European NATO, it does not, by itself, constitute evidence of strategic under- or overcontribution by countries. The question of whether the statistical concordance of ABS 4 constitutes a more comprehensive measure remains open for future research.

We argue that ABS 2 provides the closest statistical match to defense burdens within European NATO and may therefore serve as a suitable proxy when evaluating initiatives such as the ESSI, which can be seen as a functional counterpart to European NATO.

Critical Reflection When evaluating European NATO, it is essential to recognize that current military spending patterns still implicitly include the strategic backing of the US—a form of security provision that European allies have long relied upon. In the future, however, this implicit US contribution may no longer be politically assured. Consequently, its absence would require a reallocation of defense responsibilities among the existing European NATO members. The ABSs introduced in this paper provide a structured approach to allocating such costs in a more transparent and equitable manner.

The use of geographic "distance to Russia" as a proxy for threat, although intuitively appealing, is somewhat simplistic and may overlook significant nuances. Countries within the European NATO alliance vary not only in physical proximity but also in their historical experiences, political alignments, cultural ties, and exposure to hybrid threats, such as cyberattacks, disinformation campaigns, and economic coercion. For instance, historical conflicts or past occupations can heighten threat perceptions independently of geographic location, and hybrid dangers often disproportionately target politically vulnerable states regardless of their distance from Russia. Hence, future research could enhance our threat assessment by incorporating richer, multidimensional measures that reflect these diverse historical, political, cultural, and hybrid security considerations.

In this context, it is important to address a recurring critique: that countries with strong domestic defense industries may benefit disproportionately from increased military spending—an argument rooted in the concept of military Keynesianism. These industrial feedback effects are not captured in the ABS measures presented here. The empirical validity of this critique remains contested. A recent study by the Kiel Institute estimates that increasing EU defense spending from 2% to 3.5% of GDP—if allocated toward domestic high-tech production—could raise GDP by 0.9% to 1.5% annually, while also boosting innovation, exports, and industrial capacity (Ethan Ilzetzki, 2025). However, long-term studies provide a more nuanced picture. While military outlays can stimulate short-term growth and employment during wartime or crisis mobilization (e.g., WWII), their long-run macroeconomic impact is mixed. Some studies, for example, link a sustained 1% GDP increase in defense spending to a 9% slowdown in growth over a 20-year period (Dunne and Tian, 2013). Similarly, recent evidence from Germany suggests that defense spending generates relatively weak economic multipliers–at most 0.5–compared to public investment in education, infrastructure, or childcare, which can yield two to three times the initial outlay (Krebs and Kaczmarczyk, 2025). Structural bottlenecks in the German defense sector, including capacity constraints and low competition, limit productive expansion and reduce the scope for innovation-driven spillovers.

Policy Implication. The results of this paper suggest a need to reframe the policy discussion on burden-sharing. Rather than focusing on a one-size-fits-all approach like the 2% ME of GDP benchmark, policymakers should consider a broader and more economically grounded framework. This includes developing a weighted average benefit share index. The following measures could help reduce duplication, improve efficiency, and strengthen collective resilience: joint procurement, integrated R&D, strategic coordination through the European Defence Fund (EDF), Permanent Structured Cooperation (PESCO), and the ESSI, and institutionalized burden-sharing mechanisms such as transparent peer review processes—modeled after NATO's Defense Planning Capability Review or EU fiscal coordination—that assess national defense contributions against agreed-upon metrics.

Future Research. Future research should monitor defense spending trends in the coming years or employ synthetic simulations to estimate how a reduction in US military engagement would translate into increased financial burdens for European NATO. Additionally, future studies could explore the political economy of burden allocation, including domestic constraints on defense budgets, alliance bargaining processes, and the distributional consequences of different cost-sharing formulas. Finally, the development of dynamic burden-sharing models that incorporate shifting threat perceptions, strategic complementarities, and endogenous capacity building could offer more profound insight into the long-run evolution of collective defense structures.

APPENDIX | B

European NATO Burden Sharing 1993-2022

Appendix

B.1 | Illustrative Example of the Wilcoxon Signed-Rank Test

Table B.1: Illustrative Application of Wilcoxon Signed-Rank Test

Country	DB (%)	ABS (%)	Diff	Abs. Diff	Rank	Pos. Rank	Neg. Rank
A	8.0	5.0	+3.0	3.0	3.5	3.5	
B	2.5	4.0	–1.5	1.5	1		1
C	5.5	5.5	0.0^*	—	—		
D	6.0	3.0	+3.0	3.0	3.5	3.5	
E	4.0	6.5	–2.5	2.5	2		2
					Sum of ranks:	7.0	3.0

(*Notes.* This hypothetical example shows five countries' defense burden and average benefit shares in a given year. Country C is excluded due to a zero difference. Ranks are based on the absolute differences, with tied ranks averaged (3.0 and 3.0 → 3.5 each). Positive and negative ranks are listed separately. The Wilcoxon test statistic is the smaller of the positive and negative rank sums: $W = \min(7.0, 3.0) = 3.0$. A significant result indicates that countries systematically contribute more or less than their estimated benefit, suggesting potential free-riding or overcontribution.)

Steps of the Wilcoxon Signed-Rank Test (Illustrative Year):

1. Calculate each country's difference between its defense burden and estimated benefit share.

2. Exclude any observations with a zero difference (e.g., Country C), as they do not contribute to the test statistic.

3. Rank the remaining absolute differences from smallest to largest, assigning average ranks in the case of ties.

4. Assign each rank a sign based on the direction of the original difference (positive if the country over-contributes, negative if it under-contributes).

5. Separate and sum the positive and negative signed ranks. The Wilcoxon test statistic is the smaller of the two sums. In the illustrative case: $\sum$ positive ranks $= 7.0$, $\sum$ negative ranks $= 3.0$, so $W = \min(7.0, 3.0) = 3.0$.

The Wilcoxon signed-rank test is a non-parametric test that evaluates whether the median difference between two paired distributions—in this case, defense burdens and benefit shares—is statistically different from zero. In this illustrative example, the test statistic of $+3$ would be compared to a critical value or used to compute a p-value. A statistically significant result would indicate systematic imbalance between what countries contribute and what they are estimated to benefit—suggesting possible free-riding or overcontribution.

B.2 | Past Empirical Record

Table B.2: Military expenditures as a share of gross domestic product (GDP), 1993–2022

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Albania															
Belgium	1.67	1.61	1.54	1.52	1.46	1.42	1.39	1.35	1.28	1.22	1.22	1.15	1.10	1.06	1.10
Bulgaria												2.37	2.24	2.08	2.23
Canada	1.77	1.65	1.51	1.37	1.21	1.22	1.21	1.11	1.13	1.12	1.11	1.10	1.11	1.12	1.19
Croatia															
Czechia							1.84	1.86	1.74	1.81	1.88	1.70	1.78	1.57	1.42
Denmark	1.87	1.74	1.69	1.65	1.62	1.61	1.57	1.46	1.53	1.51	1.46	1.42	1.31	1.38	1.30
Estonia												1.69	1.45	1.39	1.66
France	2.72	2.69	2.52	2.44	2.39	2.25	2.20	2.09	2.04	2.05	2.10	2.11	2.03	1.98	1.91
Germany	1.69	1.54	1.49	1.46	1.41	1.39	1.39	1.35	1.31	1.31	1.30	1.25	1.05	1.18	1.15
Greece	3.14	3.12	3.10	3.24	3.30	3.46	3.66	3.63	3.35	3.15	2.56	2.67	2.90	2.83	2.72
Hungary							1.43	1.52	1.57	1.60	1.64	1.47	1.41	1.22	1.27
Italy	1.71	1.64	1.46	1.58	1.62	1.64	1.67	1.73	1.67	1.69	1.69	1.67	1.59	1.51	1.44
Latvia												1.66	1.67	1.80	1.64
Lithuania												1.19	1.16	1.17	1.11
Luxembourg	0.61	0.64	0.62	0.61	0.62	0.64	0.58	0.54	0.68	0.59	0.60	0.60	0.58	0.52	0.50
Montenegro															
Netherlands	1.99	1.88	1.77	1.73	1.64	1.56	1.57	1.43	1.43	1.41	1.43	1.42	1.39	1.39	1.35
North Macedonia															
Norway	2.63	2.68	2.31	2.16	2.02	2.16	2.04	1.70	1.70	2.08	1.97	1.84	1.58	1.44	1.46
Poland							1.89	1.82	1.89	1.89	1.90	1.86	1.92	1.91	2.00
Portugal	1.74	1.65	1.71	1.60	1.54	1.42	1.43	1.40	1.44	1.46	1.43	1.50	1.59	1.51	1.38
Romania												2.04	2.01	1.85	1.49
Slovakia												1.24	1.32	1.29	1.32
Slovenia												1.44	1.43	1.55	1.45
Spain	1.91	1.90	1.86	1.76	1.67	1.67	1.75	1.72	1.63	1.45	1.42	1.43	1.39	1.37	1.36
Turkey	3.92	4.05	3.90	4.14	4.10	3.18	3.88	3.64	3.58	3.77	3.27	2.67	2.39	2.34	2.20
United Kingdom	3.59	3.38	2.85	2.72	2.56	2.49	2.41	2.36	2.39	2.48	2.55	2.49	2.42	2.37	2.38
United States	4.62	4.23	3.87	3.57	3.42	3.21	3.10	3.12	3.14	3.46	3.85	4.04	4.09	4.04	4.07

Continued on next page

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Albania		1.52	1.56	1.53	1.49	1.41	1.35	1.16	1.10	1.11	1.14	1.27	1.29	1.24	1.20
Belgium	1.22	1.16	1.09	1.04	1.04	1.00	0.96	0.91	0.90	0.88	0.89	0.89	1.00	1.04	1.16
Bulgaria	2.13	1.74	1.64	1.31	1.33	1.45	1.31	1.24	1.24	1.21	1.45	3.15	1.58	1.51	1.59
Canada	1.25	1.38	1.19	1.19	1.12	1.00	0.99	1.15	1.16	1.35	1.32	1.28	1.39	1.26	1.18
Croatia		1.77	1.66	1.73	1.66	1.61	1.81	1.75	1.59	1.62	1.54	1.60	1.69	1.97	1.80
Czechia	1.23	1.31	1.18	1.07	1.06	1.01	0.96	0.94	0.99	0.94	1.08	1.13	1.30	1.35	1.33
Denmark	1.35	1.34	1.40	1.31	1.35	1.22	1.15	1.11	1.15	1.14	1.28	1.30	1.37	1.29	1.36
Estonia	1.77	1.80	1.70	1.67	1.88	1.88	1.89	1.99	2.03	1.96	1.97	2.00	2.26	2.01	2.13
France	1.89	2.09	1.97	1.89	1.87	1.85	1.86	1.87	1.92	1.90	1.85	1.84	1.99	1.91	1.92
Germany	1.18	1.28	1.24	1.18	1.22	1.16	1.13	1.11	1.13	1.12	1.15	1.24	1.35	1.30	1.35
Greece	3.01	3.26	2.75	2.52	2.48	2.39	2.36	2.48	2.57	2.54	2.70	2.60	3.02	3.80	4.00
Hungary	1.18	1.13	1.02	1.04	1.03	0.94	0.86	0.90	1.00	1.19	1.01	1.34	1.76	1.32	1.84
Italy	1.52	1.54	1.49	1.47	1.42	1.39	1.27	1.20	1.33	1.34	1.35	1.31	1.73	1.66	1.65
Latvia	1.70	1.42	1.11	1.12	0.94	0.97	0.98	1.07	1.49	1.64	2.13	2.09	2.22	2.16	2.25
Lithuania	1.13	1.08	0.89	0.80	0.77	0.77	0.88	1.13	1.48	1.70	1.95	1.98	2.04	1.95	2.44
Luxembourg	0.36	0.37	0.44	0.38	0.36	0.36	0.37	0.42	0.38	0.49	0.50	0.55	0.58	0.47	0.62
Montenegro										1.35	1.37	1.33	1.74	1.55	1.57
Netherlands	1.29	1.38	1.32	1.28	1.23	1.16	1.15	1.12	1.14	1.13	1.20	1.29	1.40	1.37	1.30
North Macedonia													1.24	1.47	1.58
Norway	1.37	1.60	1.51	1.44	1.39	1.41	1.46	1.50	1.62	1.71	1.71	1.85	1.97	1.68	1.46
Poland	1.75	1.79	1.84	1.79	1.80	1.79	1.91	2.13	1.94	1.87	2.02	1.96	2.26	2.22	2.21
Portugal	1.41	1.53	1.48	1.49	1.40	1.44	1.30	1.33	1.54	1.23	1.34	1.37	1.42	1.52	1.39
Romania	1.40	1.28	1.23	1.24	1.17	1.29	1.35	1.45	1.43	1.72	1.79	1.83	2.00	1.85	1.75
Slovakia	1.40	1.51	1.25	1.07	1.08	0.98	0.98	1.11	1.11	1.09	1.22	1.70	1.90	1.71	1.80
Slovenia	1.49	1.60	1.62	1.30	1.18	1.06	0.98	0.94	1.01	0.98	0.99	1.06	1.06	1.24	1.29
Spain	1.36	1.35	1.38	1.32	1.42	1.27	1.24	1.26	1.13	1.21	1.24	1.22	1.35	1.34	1.40
Turkey	2.18	2.47	2.27	2.03	2.01	1.92	1.87	1.81	2.05	2.07	2.52	2.69	2.43	1.90	1.19
United Kingdom	2.49	2.65	2.57	2.50	2.42	2.29	2.19	2.05	1.98	1.94	1.94	1.98	2.16	2.07	2.06
United States	4.45	4.88	4.90	4.82	4.46	4.02	3.68	3.46	3.40	3.30	3.30	3.41	3.65	3.40	3.31

(*Notes.* Military expenditures as a share of GDP among NATO member states, 1993–2022. This table provides a longitudinal record of defense burdens (ME/GDP) for all NATO members with available data, and serves as the empirical baseline for assessing patterns of burden sharing over time and across countries.)

B.3 European NATO Distance Categories

Table B.3: European NATO countries by distance category to Russia

Category 1: No Border with Russia	
Albania	Ireland
Austria	Italy
Belgium	Kosovo
Bosnia and Herzegovina	Luxembourg
Bulgaria	Montenegro
France	Netherlands
Greece	North Macedonia
Portugal	Serbia
Slovenia	Spain
Switzerland	United Kingdom
United States	Canada
Category 2: Indirect Border with Russia	
Czechia	Germany
Denmark	Hungary
Romania	Slovakia
Sweden	Turkey
Category 3: Direct Border with Russia	
Estonia	Finland
Latvia	Lithuania
Norway	Poland

(*Notes.* Countries are categorized based on geographic distance to Russia. Category 1 includes all others geographically more distant, such as France. Category 2 includes countries separated by only one other country (e.g., Sweden). Category 3 includes countries sharing a direct land border with Russia (e.g., Finland, Poland via Kaliningrad).)

B.4 | Evolution of Defense Burden and Average Benefit Share 2 across European NATO

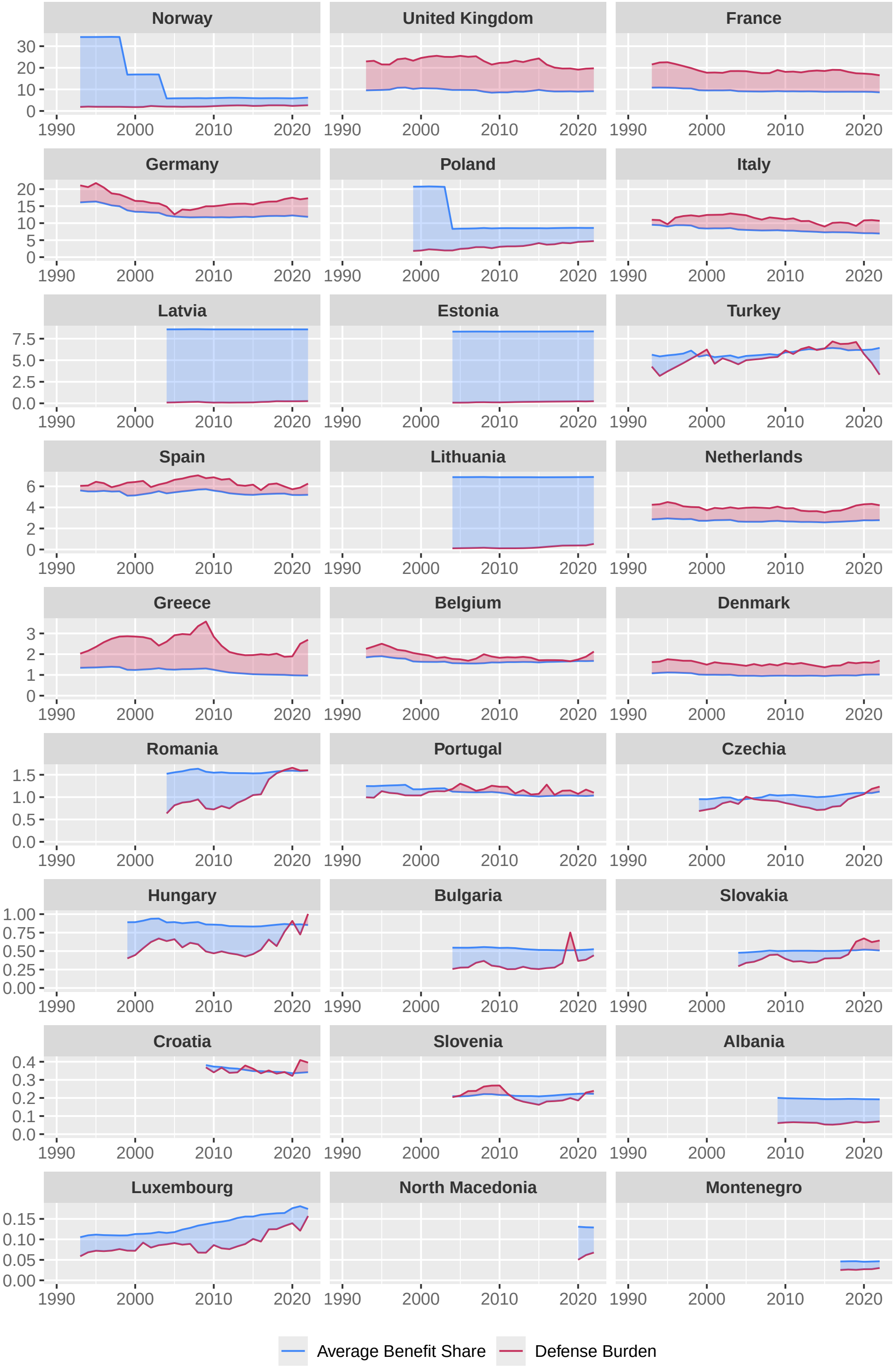


Figure B.1: The figure displays evolution of Defense Burdens (as a percentage share) for 27 European NATO members, alongside their derived Average Benefit Share 2. Each row uses a different vertical scale. The horizontal axis represents the years 1993 to 2022.

B.5 | Average Benefit Shares from 1993-2022

Table B.4: Defense burden and Average Benefit Share 4 in European NATO, based on GDP, population, and a combined threat factor including exposed borders, exposed border with Russia, and distance categories

	1993		*1994*		*1995*		*1996*		*1997*	
	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4
Albania										
Belgium	2.26	2.47	2.38	2.51	2.50	2.53	2.37	2.47	2.21	2.43
Bulgaria										
Croatia										
Czechia										
Denmark	1.62	3.14	1.64	3.16	1.75	3.18	1.72	3.17	1.68	3.16
Estonia										
France	21.54	12.06	22.46	12.08	22.57	12.05	21.75	11.93	20.81	11.69
Germany	21.10	17.89	20.59	18.03	21.79	18.13	20.48	17.60	18.75	16.99
Greece	2.03	3.61	2.16	3.62	2.35	3.62	2.57	3.64	2.74	3.66
Hungary										
Italy	10.99	11.14	10.88	11.04	9.67	10.65	11.60	11.05	12.09	11.04
Latvia										
Lithuania										
Luxembourg	0.06	0.72	0.07	0.73	0.07	0.73	0.07	0.73	0.07	0.73
Montenegro										
Netherlands	4.25	3.53	4.30	3.57	4.51	3.62	4.37	3.58	4.10	3.55
N. Macedonia										
Norway	1.91	16.99	2.05	16.99	1.97	17.01	1.97	17.04	1.95	17.07
Poland										
Portugal	1.00	2.07	0.99	2.06	1.13	2.07	1.10	2.08	1.08	2.08
Romania										
Slovakia										
Slovenia										
Spain	6.05	6.79	6.08	6.71	6.43	6.71	6.30	6.76	5.92	6.69
Turkey	4.26	7.95	3.19	7.75	3.72	7.88	4.19	7.96	4.67	8.08
UK	22.95	11.63	23.23	11.74	21.54	11.82	21.52	11.99	23.92	12.83

Continued on next page

	1998		*1999*		*2000*		*2001*		*2002*	
	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4
Albania										
Belgium	2.16	2.41	2.06	2.10	1.99	2.08	1.93	2.08	1.82	2.08
Bulgaria										
Croatia										
Czechia			0.69	1.91	0.72	1.91	0.75	1.93	0.86	1.95
Denmark	1.68	3.15	1.59	2.69	1.49	2.69	1.61	2.69	1.56	2.69
Estonia										
France	19.86	11.64	18.67	10.65	17.73	10.56	17.81	10.59	17.66	10.58
Germany	18.42	16.74	17.54	15.16	16.54	14.63	16.45	14.59	15.94	14.40
Greece	2.85	3.64	2.86	3.26	2.85	3.27	2.82	3.29	2.73	3.31
Hungary			0.40	2.01	0.45	2.01	0.54	2.03	0.62	2.05
Italy	12.29	10.94	12.01	9.93	12.41	9.84	12.44	9.90	12.48	9.89
Latvia										
Lithuania										
Luxembourg	0.08	0.73	0.07	0.55	0.07	0.56	0.09	0.56	0.08	0.56
Montenegro										
Netherlands	4.04	3.57	4.01	3.22	3.73	3.22	3.95	3.28	3.88	3.29
N. Macedonia										
Norway	1.96	17.02	1.89	10.51	1.82	10.62	1.89	10.63	2.35	10.65
Poland			1.84	10.69	1.96	10.71	2.31	10.76	2.18	10.71
Portugal	1.04	2.09	1.04	1.81	1.04	1.81	1.12	1.83	1.13	1.83
Romania										
Slovakia										
Slovenia										
Spain	6.10	6.71	6.35	6.10	6.41	6.13	6.51	6.25	5.93	6.35
Turkey	5.18	8.43	5.69	7.34	6.24	7.53	4.60	7.28	5.23	7.38
UK	24.34	12.94	23.29	12.06	24.55	12.42	25.18	12.33	25.55	12.26

Continued on next page

	2003		*2004*		*2005*		*2006*		*2007*	
	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4
Albania										
Belgium	1.86	2.09	1.77	1.85	1.75	1.84	1.68	1.84	1.78	1.84
Bulgaria			0.26	0.91	0.28	0.91	0.28	0.91	0.34	0.91
Croatia										
Czechia	0.90	1.95	0.85	1.55	1.01	1.55	0.96	1.60	0.93	1.62
Denmark	1.53	2.69	1.49	2.24	1.44	2.26	1.52	2.24	1.44	2.23
Estonia			0.09	4.09	0.08	4.10	0.09	4.09	0.13	4.10
France	18.47	10.66	18.49	9.97	18.40	9.92	17.88	9.86	17.49	9.82
Germany	15.80	14.33	14.85	13.14	12.56	12.86	14.01	12.72	13.84	12.61
Greece	2.41	3.35	2.60	2.99	2.91	2.96	2.97	2.99	2.94	3.00
Hungary	0.67	2.06	0.64	1.65	0.66	1.55	0.55	1.64	0.61	1.65
Italy	12.84	9.96	12.56	9.26	12.32	9.16	11.57	9.08	11.03	9.00
Latvia			0.10	3.91	0.11	3.91	0.14	3.91	0.17	3.92
Lithuania			0.11	3.40	0.13	3.40	0.14	3.40	0.15	3.41
Luxembourg	0.09	0.56	0.09	0.39	0.09	0.40	0.09	0.40	0.09	0.41
Montenegro										
Netherlands	4.00	3.31	3.89	2.98	3.96	2.96	3.99	2.96	3.96	2.96
N. Macedonia										
Norway	2.16	10.63	2.03	6.13	2.02	6.27	1.96	6.24	2.03	6.24
Poland	1.99	10.63	1.98	5.83	2.44	5.85	2.58	5.94	2.96	5.98
Portugal	1.13	1.84	1.18	1.58	1.30	1.58	1.23	1.57	1.14	1.56
Romania			0.64	2.28	0.82	2.32	0.88	2.34	0.90	2.38
Slovakia			0.30	1.04	0.34	1.05	0.36	1.05	0.39	1.06
Slovenia			0.20	0.58	0.21	0.58	0.24	0.58	0.24	0.59
Spain	6.17	6.53	6.34	6.11	6.63	6.22	6.74	6.30	6.92	6.38
Turkey	4.92	7.48	4.53	6.79	5.00	7.00	5.09	7.06	5.17	7.12
UK	25.06	11.93	25.02	11.31	25.53	11.34	25.07	11.29	25.34	11.22

Continued on next page

	2008		*2009*		*2010*		*2011*		*2012*	
	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4
Albania			0.06	0.54	0.06	0.54	0.07	0.54	0.07	0.54
Belgium	1.99	1.85	1.89	1.87	1.82	1.87	1.85	1.89	1.84	1.89
Bulgaria	0.37	0.92	0.30	0.89	0.29	0.89	0.26	0.89	0.26	0.89
Croatia			0.37	1.30	0.34	1.32	0.37	1.32	0.34	1.31
Czechia	0.92	1.67	0.91	1.62	0.87	1.61	0.83	1.62	0.79	1.60
Denmark	1.52	2.24	1.46	2.17	1.57	2.19	1.52	2.19	1.57	2.19
Estonia	0.14	4.10	0.12	4.03	0.12	4.04	0.13	4.04	0.16	4.04
France	17.54	9.91	18.95	9.97	18.11	9.88	18.23	9.91	17.86	9.85
Germany	14.29	12.64	14.95	12.63	14.97	12.59	15.21	12.62	15.58	12.57
Greece	3.35	3.02	3.57	2.92	2.84	2.84	2.40	2.77	2.10	2.71
Hungary	0.59	1.66	0.50	1.58	0.47	1.45	0.50	1.44	0.47	1.43
Italy	11.67	9.02	11.43	8.99	11.14	8.87	11.39	8.85	10.59	8.68
Latvia	0.18	3.93	0.12	3.87	0.09	3.86	0.10	3.86	0.09	3.86
Lithuania	0.17	3.41	0.14	3.35	0.11	3.35	0.12	3.35	0.12	3.35
Luxembourg	0.07	0.41	0.07	0.40	0.09	0.41	0.08	0.41	0.08	0.41
Montenegro										
Netherlands	3.92	3.02	4.07	3.03	3.90	2.98	3.92	2.97	3.69	2.93
N. Macedonia										
Norway	2.02	6.29	2.08	6.01	2.26	6.19	2.44	6.26	2.54	6.33
Poland	2.96	6.10	2.65	5.93	3.06	5.93	3.18	5.95	3.20	5.94
Portugal	1.18	1.57	1.25	1.55	1.23	1.54	1.23	1.51	1.08	1.48
Romania	0.95	2.39	0.75	2.29	0.73	2.27	0.80	2.28	0.75	2.26
Slovakia	0.45	1.07	0.45	1.04	0.40	1.04	0.36	1.04	0.36	1.04
Slovenia	0.26	0.59	0.27	0.57	0.27	0.51	0.22	0.51	0.19	0.51
Spain	7.04	6.47	6.77	6.46	6.86	6.35	6.63	6.25	6.71	6.09
Turkey	5.32	7.21	5.39	7.03	6.14	7.34	5.73	7.39	6.29	7.60
UK	23.10	10.50	21.49	9.95	22.26	10.15	22.42	10.13	23.28	10.49

Continued on next page

	2013		*2014*		*2015*		*2016*		*2017*	
	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4
Albania	0.06	0.54	0.06	0.54	0.05	0.54	0.05	0.54	0.06	0.51
Belgium	1.87	1.90	1.83	1.89	1.70	1.87	1.71	1.90	1.71	1.90
Bulgaria	0.29	0.88	0.26	0.88	0.26	0.87	0.27	0.87	0.28	0.87
Croatia	0.34	1.31	0.38	1.30	0.36	1.29	0.34	1.29	0.35	1.28
Czechia	0.76	1.58	0.71	1.57	0.72	1.57	0.79	1.59	0.80	1.60
Denmark	1.50	2.20	1.43	2.19	1.36	2.18	1.45	2.20	1.45	2.19
Estonia	0.17	4.05	0.18	4.05	0.19	4.05	0.20	4.05	0.21	4.03
France	18.46	9.89	18.71	9.81	18.51	9.67	19.06	9.71	18.99	9.69
Germany	15.71	12.66	15.73	12.73	15.48	12.64	16.06	12.87	16.32	12.96
Greece	2.01	2.68	1.95	2.65	1.95	2.63	2.00	2.62	1.96	2.60
Hungary	0.45	1.43	0.43	1.42	0.46	1.42	0.52	1.42	0.66	1.42
Italy	10.64	8.64	9.76	8.57	9.00	8.43	10.07	8.48	10.21	8.44
Latvia	0.10	3.86	0.10	3.86	0.11	3.86	0.16	3.86	0.19	3.84
Lithuania	0.13	3.35	0.15	3.35	0.19	3.35	0.26	3.35	0.31	3.33
Luxembourg	0.08	0.42	0.09	0.42	0.10	0.42	0.09	0.42	0.12	0.42
Montenegro									0.03	0.38
Netherlands	3.63	2.93	3.64	2.91	3.52	2.88	3.67	2.92	3.70	2.94
N. Macedonia										
Norway	2.62	6.32	2.58	6.25	2.36	6.15	2.41	6.11	2.65	6.11
Poland	3.29	5.92	3.64	5.93	4.14	5.92	3.69	5.90	3.81	5.93
Portugal	1.16	1.47	1.06	1.46	1.07	1.45	1.28	1.46	1.05	1.46
Romania	0.87	2.26	0.95	2.26	1.05	2.25	1.06	2.26	1.40	2.26
Slovakia	0.34	1.04	0.35	1.04	0.40	1.04	0.40	1.04	0.40	1.03
Slovenia	0.18	0.51	0.17	0.51	0.16	0.51	0.18	0.51	0.18	0.51
Spain	6.12	6.02	6.05	5.96	6.16	5.94	5.64	5.99	6.19	6.02
Turkey	6.54	7.71	6.19	7.67	6.35	7.79	7.17	7.84	6.88	7.76
UK	22.66	10.43	23.59	10.79	24.33	11.29	21.46	10.80	20.10	10.53

Continued on next page

	2018		*2019*		*2020*		*2021*		*2022*	
	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4	DB	ABS 4
Albania	0.06	0.52	0.07	0.52	0.06	0.49	0.07	0.49	0.07	0.49
Belgium	1.70	1.91	1.66	1.92	1.74	1.93	1.88	1.93	2.12	1.93
Bulgaria	0.34	0.87	0.75	0.87	0.37	0.85	0.38	0.86	0.44	0.85
Croatia	0.33	1.28	0.34	1.28	0.32	1.27	0.41	1.27	0.40	1.27
Czechia	0.95	1.63	1.01	1.65	1.07	1.64	1.18	1.64	1.23	1.67
Denmark	1.60	2.19	1.56	2.18	1.60	2.21	1.59	2.22	1.69	2.22
Estonia	0.22	4.03	0.22	4.04	0.24	4.02	0.23	4.02	0.25	4.03
France	18.09	9.70	17.44	9.69	17.31	9.69	17.04	9.63	16.53	9.41
Germany	16.36	12.99	17.08	12.94	17.49	13.11	17.00	12.90	17.30	12.70
Greece	2.03	2.59	1.87	2.58	1.89	2.54	2.50	2.54	2.70	2.53
Hungary	0.57	1.43	0.76	1.44	0.91	1.42	0.72	1.43	1.00	1.42
Italy	10.00	8.39	9.18	8.26	10.80	8.13	10.90	8.13	10.69	8.04
Latvia	0.25	3.84	0.24	3.84	0.24	3.83	0.25	3.83	0.26	3.83
Lithuania	0.37	3.33	0.38	3.33	0.39	3.32	0.39	3.33	0.53	3.34
Luxembourg	0.13	0.42	0.13	0.42	0.14	0.43	0.12	0.43	0.16	0.43
Montenegro	0.03	0.38	0.03	0.38	0.03	0.37	0.03	0.37	0.03	0.37
Netherlands	3.91	2.98	4.18	3.01	4.29	3.07	4.33	3.07	4.20	3.08
N. Macedonia					0.05	0.41	0.06	0.41	0.07	0.41
Norway	2.65	6.12	2.62	6.08	2.37	6.02	2.54	6.16	2.68	6.33
Poland	4.24	5.97	4.10	6.00	4.50	6.01	4.60	5.96	4.73	5.97
Portugal	1.14	1.46	1.15	1.47	1.07	1.45	1.17	1.45	1.10	1.46
Romania	1.53	2.28	1.61	2.30	1.66	2.29	1.59	2.28	1.60	2.30
Slovakia	0.46	1.04	0.63	1.04	0.67	1.03	0.62	1.03	0.64	1.02
Slovenia	0.19	0.51	0.20	0.51	0.19	0.51	0.23	0.51	0.24	0.51
Spain	6.27	6.04	5.98	6.05	5.72	5.91	5.88	5.91	6.26	5.93
Turkey	6.92	7.55	7.11	7.60	5.73	7.58	4.68	7.63	3.32	7.82
UK	19.65	10.53	19.69	10.60	19.14	10.47	19.60	10.59	19.75	10.65

(*Notes.* The table reports the defense burden (measured as military expenditure over GDP) and the Average Benefit Share 4 for European NATO from 1993 to 2022. The benefit share is derived from a weighted composite of GDP, population size, and including three threat dimensions: exposed land borders, exposed borders with Russia, and a distance category. Each component is equally weighted in constructing the composite measure. Values are expressed as shares that sum to 100% across countries per year.)

Table B.5: Defense burden and Average Benefit Shares 1-3 in European NATO based on GDP, population, and exposed borders (EB), exposed borders with Russia (EBR), or distance categories (DC)

	1995				2000				2005			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania												
Belgium	2.50	1.93	1.90	3.76	1.99	1.65	1.63	2.97	1.75	1.58	1.56	2.39
Bulgaria									0.28	0.81	0.55	1.38
Croatia												
Czechia					0.72	1.16	0.95	3.62	1.01	1.08	0.96	2.62
Denmark	1.75	3.59	1.12	4.82	1.49	3.39	1.01	3.68	1.44	3.19	0.96	2.63
Estonia									0.08	1.37	8.32	2.62
France	22.57	12.66	10.82	12.67	17.73	11.29	9.52	10.86	18.40	10.75	9.09	9.93
Germany	21.79	17.96	16.36	20.07	16.54	14.51	13.36	16.03	12.56	13.02	11.94	13.61
Greece	2.35	6.29	1.36	3.21	2.85	5.99	1.24	2.57	2.91	5.55	1.25	2.09
Hungary					0.45	1.58	0.89	3.56	0.66	1.19	0.89	2.56
Italy	9.67	12.05	9.02	10.88	12.41	11.34	8.42	9.76	12.32	10.66	8.00	8.83
Latvia									0.11	0.48	8.58	2.68
Lithuania									0.13	0.57	6.87	2.77
Luxembourg	0.07	0.11	0.11	1.96	0.07	0.11	0.11	1.45	0.09	0.12	0.12	0.95
Montenegro												
Netherlands	4.51	3.11	2.95	4.81	3.73	2.88	2.73	4.06	3.96	2.77	2.64	3.47
N. Macedonia												
Norway	1.97	10.29	34.26	6.48	1.82	10.00	16.90	4.98	2.02	9.45	5.85	3.52
Poland					1.96	4.06	20.74	7.32	2.44	3.58	8.38	5.59
Portugal	1.13	1.86	1.25	3.11	1.04	1.76	1.17	2.51	1.30	1.66	1.12	1.95
Romania									0.82	2.18	1.55	3.22
Slovakia									0.34	0.51	0.48	2.15
Slovenia									0.21	0.50	0.21	1.04
Spain	6.43	7.23	5.52	7.37	6.41	6.78	5.14	6.47	6.63	6.97	5.43	6.27
Turkey	3.72	8.81	5.56	9.27	6.24	8.73	5.60	8.27	5.00	8.35	5.49	7.16
UK	21.54	14.12	9.75	11.60	24.55	14.77	10.57	11.90	25.53	13.68	9.75	10.58

Continued on next page

	2010				2015				2020			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania	0.06	0.44	0.20	0.99	0.05	0.43	0.19	0.99	0.06	0.33	0.19	0.95
Belgium	1.82	1.62	1.60	2.39	1.70	1.62	1.60	2.40	1.74	1.69	1.67	2.43
Bulgaria	0.29	0.79	0.54	1.34	0.26	0.77	0.53	1.32	0.37	0.73	0.53	1.29
Croatia	0.34	2.41	0.37	1.17	0.36	2.39	0.35	1.14	0.32	2.37	0.34	1.09
Czechia	0.87	1.16	1.04	2.63	0.72	1.12	1.01	2.59	1.07	1.21	1.09	2.61
Denmark	1.57	3.06	0.97	2.55	1.36	3.04	0.95	2.54	1.60	3.10	1.01	2.53
Estonia	0.12	1.30	8.32	2.50	0.19	1.30	8.33	2.51	0.24	1.31	8.34	2.41
France	18.11	10.66	9.10	9.89	18.51	10.44	8.89	9.68	17.31	10.48	8.92	9.68
Germany	14.97	12.73	11.72	13.31	15.48	12.79	11.77	13.36	17.49	13.28	12.27	13.78
Greece	2.84	5.23	1.25	2.04	1.95	5.02	1.03	1.83	1.89	4.90	0.98	1.74
Hungary	0.47	1.04	0.86	2.45	0.46	1.01	0.83	2.42	0.91	1.04	0.86	2.38
Italy	11.14	10.27	7.77	8.56	9.00	9.83	7.33	8.12	10.80	9.55	7.05	7.80
Latvia	0.09	0.46	8.57	2.55	0.11	0.45	8.57	2.55	0.24	0.46	8.58	2.45
Lithuania	0.11	0.54	6.86	2.64	0.19	0.54	6.86	2.64	0.39	0.55	6.88	2.54
Luxembourg	0.09	0.14	0.14	0.93	0.10	0.16	0.16	0.95	0.14	0.18	0.18	0.93
Montenegro									0.03	0.26	0.04	0.80
Netherlands	3.90	2.80	2.67	3.47	3.52	2.70	2.58	3.37	4.29	2.90	2.77	3.53
N. Macedonia									0.05	0.21	0.13	0.89
Norway	2.26	9.08	5.97	3.52	2.36	9.03	5.93	3.48	2.37	8.93	5.84	3.28
Poland	3.06	3.68	8.51	5.60	4.14	3.67	8.50	5.60	4.50	3.79	8.63	5.61
Portugal	1.23	1.62	1.10	1.90	1.07	1.53	1.01	1.81	1.07	1.54	1.03	1.79
Romania	0.73	2.13	1.55	3.14	1.05	2.11	1.53	3.12	1.66	2.17	1.59	3.11
Slovakia	0.40	0.53	0.50	2.09	0.40	0.53	0.50	2.09	0.67	0.55	0.52	2.03
Slovenia	0.27	0.32	0.22	1.01	0.16	0.31	0.21	1.00	0.19	0.32	0.22	0.98
Spain	6.86	7.04	5.60	6.39	6.16	6.63	5.19	5.98	5.72	6.62	5.18	5.94
Turkey	6.14	8.60	5.91	7.50	6.35	9.05	6.37	7.95	5.73	8.86	6.18	7.70
UK	22.26	12.35	8.65	9.44	24.33	13.49	9.79	10.58	19.14	12.68	8.98	9.74

(*Notes.* The table displays defense burdens (measured as military expenditure over GDP) and alternative Average Benefit Shares (ABS) for European NATO for selected years (1995, 2000, 2005, 2010, 2015, 2020) to illustrate changes over time. Each ABS combines GDP, population, and a threat component with equal weights. ABS 1 uses total exposed land borders; ABS 2 uses only exposed borders with Russia; and ABS DC is based on distance category. All values are expressed as percentage shares summing to 100% across countries in each year.)

Table B.6: Defense burden and Average Benefit Shares 1-3 in European NATO based on GDP, population, and EB, EBR, or DC

	1993				1994				1995				1996			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania																
Belgium	2.26	1.87	1.85	3.70	2.38	1.91	1.89	3.74	2.50	1.93	1.90	3.76	2.37	1.87	1.85	3.70
Bulgaria																
Croatia																
Czechia																
Denmark	1.62	3.55	1.08	4.78	1.64	3.57	1.10	4.81	1.75	3.59	1.12	4.82	1.72	3.59	1.11	4.82
Estonia																
France	21.54	12.67	10.83	12.68	22.46	12.69	10.85	12.71	22.57	12.66	10.82	12.67	21.75	12.54	10.70	12.55
Germany	21.10	17.72	16.12	19.83	20.59	17.86	16.26	19.97	21.79	17.96	16.36	20.07	20.48	17.42	15.83	19.54
Greece	2.03	6.28	1.34	3.20	2.16	6.29	1.35	3.21	2.35	6.29	1.36	3.21	2.57	6.31	1.38	3.23
Hungary																
Italy	10.99	12.54	9.52	11.37	10.88	12.44	9.41	11.27	9.67	12.05	9.02	10.88	11.60	12.45	9.42	11.27
Latvia																
Lithuania																
Luxembourg	0.06	0.11	0.11	1.96	0.07	0.11	0.11	1.96	0.07	0.11	0.11	1.96	0.07	0.11	0.11	1.96
Montenegro																
Netherlands	4.25	3.02	2.87	4.72	4.30	3.06	2.90	4.76	4.51	3.11	2.95	4.81	4.37	3.07	2.91	4.77
N. Macedonia																
Norway	1.91	10.27	34.24	6.46	2.05	10.27	34.24	6.46	1.97	10.29	34.26	6.48	1.97	10.32	34.29	6.51
Poland																
Portugal	1.00	1.85	1.25	3.10	0.99	1.85	1.25	3.10	1.13	1.86	1.25	3.11	1.10	1.87	1.26	3.11
Romania																
Slovakia																
Slovenia																
Spain	6.05	7.31	5.61	7.46	6.08	7.23	5.52	7.37	6.43	7.23	5.52	7.37	6.30	7.28	5.57	7.43
Turkey	4.26	8.88	5.64	9.34	3.19	8.68	5.44	9.14	3.72	8.81	5.56	9.27	4.19	8.89	5.65	9.35
UK	22.95	13.93	9.56	11.41	23.23	14.03	9.67	11.52	21.54	14.12	9.75	11.60	21.52	14.28	9.91	11.76

Continued on next page

	1997				1998				1999				2000			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania																
Belgium	2.21	1.82	1.80	3.65	2.16	1.81	1.78	3.64	2.06	1.67	1.65	2.98	1.99	1.65	1.63	2.97
Bulgaria																
Croatia																
Czechia									0.69	1.16	0.95	3.62	0.72	1.16	0.95	3.62
Denmark	1.68	3.57	1.10	4.80	1.68	3.56	1.09	4.79	1.59	3.37	1.02	3.68	1.49	3.39	1.01	3.68
Estonia																
France	20.81	12.30	10.46	12.31	19.86	12.25	10.41	12.27	18.67	11.37	9.62	10.95	17.73	11.29	9.52	10.86
Germany	18.75	16.82	15.23	18.93	18.42	16.57	14.97	18.68	17.54	15.28	13.77	16.44	16.54	14.51	13.36	16.03
Greece	2.74	6.33	1.39	3.25	2.85	6.31	1.38	3.23	2.86	5.94	1.25	2.58	2.85	5.99	1.24	2.57
Hungary									0.40	1.57	0.89	3.56	0.45	1.58	0.89	3.56
Italy	12.09	12.44	9.41	11.26	12.29	12.34	9.31	11.16	12.01	11.41	8.53	9.86	12.41	11.34	8.42	9.76
Latvia																
Lithuania																
Luxembourg	0.07	0.11	0.11	1.96	0.08	0.11	0.11	1.96	0.07	0.11	0.11	1.44	0.07	0.11	0.11	1.45
Montenegro																
Netherlands	4.10	3.03	2.88	4.73	4.04	3.05	2.90	4.75	4.01	2.88	2.73	4.06	3.73	2.88	2.73	4.06
N. Macedonia																
Norway	1.95	10.35	34.32	6.54	1.96	10.30	34.27	6.49	1.89	9.82	16.82	4.90	1.82	10.00	16.90	4.98
Poland									1.84	4.03	20.73	7.31	1.96	4.06	20.74	7.32
Portugal	1.08	1.87	1.27	3.12	1.04	1.88	1.27	3.13	1.04	1.75	1.17	2.51	1.04	1.76	1.17	2.51
Romania																
Slovakia																
Slovenia																
Spain	5.92	7.21	5.51	7.36	6.10	7.23	5.53	7.38	6.35	6.74	5.12	6.45	6.41	6.78	5.14	6.47
Turkey	4.67	9.01	5.77	9.47	5.18	9.36	6.11	9.82	5.69	8.51	5.42	8.09	6.24	8.73	5.60	8.27
UK	23.92	15.13	10.76	12.61	24.34	15.23	10.87	12.72	23.29	14.38	10.23	11.56	24.55	14.77	10.57	11.90

Continued on next page

	2001				2002				2003				2004			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania																
Belgium	1.93	1.65	1.63	2.96	1.82	1.65	1.63	2.96	1.86	1.66	1.64	2.97	1.77	1.59	1.57	2.40
Bulgaria													0.26	0.80	0.55	1.38
Croatia																
Czechia	0.75	1.18	0.97	3.64	0.86	1.20	0.99	3.66	0.90	1.20	0.99	3.66	0.85	1.12	0.93	2.60
Denmark	1.61	3.39	1.01	3.68	1.56	3.38	1.00	3.67	1.53	3.39	1.01	3.67	1.49	3.13	0.96	2.63
Estonia													0.09	1.34	8.32	2.62
France	17.81	11.32	9.55	10.89	17.66	11.31	9.54	10.88	18.47	11.39	9.62	10.96	18.49	10.77	9.15	9.99
Germany	16.45	14.46	13.31	15.98	15.94	14.28	13.13	15.80	15.80	14.21	13.06	15.72	14.85	13.28	12.23	13.90
Greece	2.82	6.01	1.26	2.59	2.73	6.03	1.28	2.62	2.41	6.07	1.32	2.66	2.60	5.59	1.27	2.10
Hungary	0.54	1.60	0.91	3.58	0.62	1.62	0.94	3.60	0.67	1.63	0.94	3.61	0.64	1.51	0.89	2.56
Italy	12.44	11.39	8.48	9.81	12.48	11.39	8.47	9.80	12.84	11.46	8.55	9.88	12.56	10.76	8.10	8.94
Latvia													0.10	0.47	8.58	2.68
Lithuania													0.11	0.56	6.87	2.77
Luxembourg	0.09	0.11	0.11	1.45	0.08	0.11	0.11	1.45	0.09	0.12	0.12	1.45	0.09	0.12	0.12	0.95
Montenegro																
Netherlands	3.95	2.93	2.79	4.12	3.88	2.94	2.80	4.13	4.00	2.96	2.81	4.15	3.89	2.79	2.66	3.49
N. Macedonia																
Norway	1.89	10.01	16.90	4.99	2.35	10.03	16.92	5.01	2.16	10.00	16.90	4.98	2.03	9.16	5.78	3.45
Poland	2.31	4.11	20.80	7.38	2.18	4.06	20.75	7.33	1.99	3.98	20.66	7.25	1.98	3.68	8.31	5.52
Portugal	1.12	1.77	1.19	2.52	1.13	1.78	1.19	2.53	1.13	1.78	1.20	2.53	1.18	1.66	1.12	1.96
Romania													0.64	2.13	1.52	3.19
Slovakia													0.30	0.51	0.48	2.14
Slovenia													0.20	0.49	0.21	1.04
Spain	6.51	6.90	5.25	6.59	5.93	7.00	5.36	6.69	6.17	7.18	5.54	6.87	6.34	6.83	5.33	6.17
Turkey	4.60	8.48	5.35	8.02	5.23	8.58	5.45	8.12	4.92	8.67	5.55	8.22	4.53	8.14	5.29	6.96
UK	25.18	14.69	10.48	11.82	25.55	14.62	10.42	11.75	25.06	14.29	10.09	11.42	25.02	13.59	9.76	10.59

Continued on next page

	2005				2006				2007				2008			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania																
Belgium	1.75	1.58	1.56	2.39	1.68	1.57	1.55	2.39	1.78	1.57	1.55	2.39	1.99	1.59	1.57	2.40
Bulgaria	0.28	0.81	0.55	1.38	0.28	0.80	0.55	1.38	0.34	0.80	0.55	1.38	0.37	0.81	0.55	1.39
Croatia																
Czechia	1.01	1.08	0.96	2.62	0.96	1.17	0.98	2.64	0.93	1.19	1.00	2.66	0.92	1.24	1.05	2.72
Denmark	1.44	3.19	0.96	2.63	1.52	3.13	0.96	2.63	1.44	3.11	0.95	2.61	1.52	3.13	0.96	2.63
Estonia	0.08	1.37	8.32	2.62	0.09	1.34	8.32	2.62	0.13	1.35	8.33	2.63	0.14	1.35	8.33	2.62
France	18.40	10.75	9.09	9.93	17.88	10.66	9.05	9.88	17.49	10.62	9.01	9.84	17.54	10.71	9.10	9.93
Germany	12.56	13.02	11.94	13.61	14.01	12.86	11.81	13.48	13.84	12.76	11.71	13.38	14.29	12.79	11.74	13.41
Greece	2.91	5.55	1.25	2.09	2.97	5.60	1.27	2.11	2.94	5.60	1.28	2.11	3.35	5.62	1.30	2.13
Hungary	0.66	1.19	0.89	2.56	0.55	1.50	0.88	2.54	0.61	1.51	0.89	2.55	0.59	1.52	0.89	2.56
Italy	12.32	10.66	8.00	8.83	11.57	10.57	7.91	8.75	11.03	10.49	7.84	8.67	11.67	10.52	7.86	8.69
Latvia	0.11	0.48	8.58	2.68	0.14	0.48	8.59	2.68	0.17	0.49	8.59	2.69	0.18	0.49	8.60	2.69
Lithuania	0.13	0.57	6.87	2.77	0.14	0.56	6.87	2.77	0.15	0.57	6.88	2.77	0.17	0.57	6.89	2.78
Luxembourg	0.09	0.12	0.12	0.95	0.09	0.12	0.12	0.96	0.09	0.13	0.13	0.96	0.07	0.13	0.13	0.97
Montenegro																
Netherlands	3.96	2.77	2.64	3.47	3.99	2.77	2.64	3.47	3.96	2.77	2.64	3.47	3.92	2.83	2.69	3.53
N. Macedonia																
Norway	2.02	9.45	5.85	3.52	1.96	9.27	5.89	3.55	2.03	9.27	5.89	3.56	2.02	9.32	5.95	3.61
Poland	2.44	3.58	8.38	5.59	2.58	3.78	8.41	5.62	2.96	3.83	8.46	5.67	2.96	3.94	8.57	5.78
Portugal	1.30	1.66	1.12	1.95	1.23	1.64	1.11	1.94	1.14	1.64	1.11	1.94	1.18	1.64	1.11	1.94
Romania	0.82	2.18	1.55	3.22	0.88	2.18	1.58	3.24	0.90	2.22	1.62	3.28	0.95	2.24	1.64	3.30
Slovakia	0.34	0.51	0.48	2.15	0.36	0.52	0.49	2.15	0.39	0.52	0.50	2.16	0.45	0.54	0.51	2.17
Slovenia	0.21	0.50	0.21	1.04	0.24	0.49	0.21	1.04	0.24	0.50	0.22	1.05	0.26	0.50	0.22	1.05
Spain	6.63	6.97	5.43	6.27	6.74	7.02	5.53	6.36	6.92	7.10	5.60	6.43	7.04	7.19	5.70	6.53
Turkey	5.00	8.35	5.49	7.16	5.09	8.40	5.55	7.22	5.17	8.46	5.62	7.28	5.32	8.55	5.71	7.37
UK	25.53	13.68	9.75	10.58	25.07	13.56	9.74	10.57	25.34	13.50	9.67	10.50	23.10	12.77	8.95	9.78

Continued on next page

	2009				2010				2011				2012			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania	0.06	0.43	0.20	0.99	0.06	0.44	0.20	0.99	0.07	0.44	0.20	0.99	0.07	0.44	0.20	0.99
Belgium	1.89	1.62	1.60	2.40	1.82	1.62	1.60	2.39	1.85	1.64	1.62	2.41	1.84	1.64	1.62	2.41
Bulgaria	0.30	0.79	0.55	1.34	0.29	0.79	0.54	1.34	0.26	0.79	0.54	1.34	0.26	0.79	0.54	1.33
Croatia	0.37	2.35	0.38	1.18	0.34	2.41	0.37	1.17	0.37	2.41	0.37	1.16	0.34	2.41	0.36	1.16
Czechia	0.91	1.21	1.04	2.62	0.87	1.16	1.04	2.63	0.83	1.16	1.05	2.64	0.79	1.15	1.03	2.62
Denmark	1.46	2.99	0.97	2.55	1.57	3.06	0.97	2.55	1.52	3.05	0.96	2.55	1.57	3.06	0.96	2.55
Estonia	0.12	1.26	8.32	2.50	0.12	1.30	8.32	2.50	0.13	1.30	8.32	2.50	0.16	1.30	8.32	2.50
France	18.95	10.71	9.20	10.00	18.11	10.66	9.10	9.89	18.23	10.69	9.13	9.92	17.86	10.62	9.07	9.86
Germany	14.95	12.75	11.77	13.36	14.97	12.73	11.72	13.31	15.21	12.77	11.76	13.35	15.58	12.72	11.70	13.29
Greece	3.57	5.35	1.31	2.10	2.84	5.23	1.25	2.04	2.40	5.16	1.18	1.97	2.10	5.10	1.12	1.91
Hungary	0.50	1.44	0.86	2.45	0.47	1.04	0.86	2.45	0.50	1.03	0.86	2.44	0.47	1.01	0.84	2.43
Italy	11.43	10.38	7.90	8.69	11.14	10.27	7.77	8.56	11.39	10.25	7.75	8.54	10.59	10.08	7.58	8.37
Latvia	0.12	0.45	8.58	2.56	0.09	0.46	8.57	2.55	0.10	0.46	8.57	2.55	0.09	0.46	8.58	2.55
Lithuania	0.14	0.54	6.87	2.65	0.11	0.54	6.86	2.64	0.12	0.54	6.87	2.64	0.12	0.54	6.87	2.64
Luxembourg	0.07	0.14	0.14	0.93	0.09	0.14	0.14	0.93	0.08	0.14	0.14	0.94	0.08	0.15	0.15	0.94
Montenegro																
Netherlands	4.07	2.85	2.72	3.52	3.90	2.80	2.67	3.47	3.92	2.79	2.66	3.45	3.69	2.75	2.62	3.42
N. Macedonia																
Norway	2.08	8.72	5.89	3.43	2.26	9.08	5.97	3.52	2.44	9.15	6.04	3.59	2.54	9.22	6.12	3.66
Poland	2.65	3.79	8.45	5.54	3.06	3.68	8.51	5.60	3.18	3.70	8.53	5.62	3.20	3.69	8.52	5.61
Portugal	1.25	1.61	1.12	1.91	1.23	1.62	1.10	1.90	1.23	1.59	1.08	1.87	1.08	1.56	1.04	1.84
Romania	0.75	2.13	1.57	3.16	0.73	2.13	1.55	3.14	0.80	2.14	1.56	3.14	0.75	2.13	1.54	3.13
Slovakia	0.45	0.53	0.50	2.09	0.40	0.53	0.50	2.09	0.36	0.53	0.50	2.09	0.36	0.53	0.50	2.09
Slovenia	0.27	0.48	0.22	1.01	0.27	0.32	0.22	1.01	0.22	0.32	0.22	1.01	0.19	0.31	0.21	1.00
Spain	6.77	7.13	5.73	6.53	6.86	7.04	5.60	6.39	6.63	6.95	5.50	6.30	6.71	6.79	5.34	6.14
Turkey	5.39	8.27	5.61	7.20	6.14	8.60	5.91	7.50	5.73	8.66	5.97	7.56	6.29	8.86	6.18	7.76
UK	21.49	12.07	8.49	9.29	22.26	12.35	8.65	9.44	22.42	12.33	8.63	9.42	23.28	12.70	9.00	9.79

Continued on next page

	2013				2014				2015				2016			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania	0.06	0.44	0.20	0.99	0.06	0.44	0.19	0.99	0.05	0.43	0.19	0.99	0.05	0.43	0.19	0.99
Belgium	1.87	1.65	1.63	2.42	1.83	1.64	1.62	2.42	1.70	1.62	1.60	2.40	1.71	1.65	1.63	2.42
Bulgaria	0.29	0.78	0.53	1.33	0.26	0.78	0.53	1.32	0.26	0.77	0.53	1.32	0.27	0.77	0.53	1.32
Croatia	0.34	2.40	0.36	1.16	0.38	2.40	0.35	1.15	0.36	2.39	0.35	1.14	0.34	2.39	0.35	1.14
Czechia	0.76	1.13	1.02	2.60	0.71	1.11	1.00	2.59	0.72	1.12	1.01	2.59	0.79	1.14	1.02	2.61
Denmark	1.50	3.06	0.97	2.55	1.43	3.06	0.96	2.55	1.36	3.04	0.95	2.54	1.45	3.06	0.97	2.56
Estonia	0.17	1.31	8.33	2.51	0.18	1.31	8.33	2.51	0.19	1.30	8.33	2.51	0.20	1.31	8.33	2.51
France	18.46	10.66	9.10	9.89	18.71	10.58	9.03	9.82	18.51	10.44	8.89	9.68	19.06	10.48	8.92	9.72
Germany	15.71	12.81	11.80	13.38	15.73	12.88	11.86	13.45	15.48	12.79	11.77	13.36	16.06	13.02	12.00	13.59
Greece	2.01	5.07	1.09	1.88	1.95	5.05	1.06	1.86	1.95	5.02	1.03	1.83	2.00	5.01	1.02	1.82
Hungary	0.45	1.01	0.84	2.42	0.43	1.01	0.84	2.42	0.46	1.01	0.83	2.42	0.52	1.01	0.84	2.42
Italy	10.64	10.04	7.54	8.33	9.76	9.98	7.47	8.27	9.00	9.83	7.33	8.12	10.07	9.89	7.38	8.18
Latvia	0.10	0.46	8.58	2.55	0.10	0.46	8.57	2.55	0.11	0.45	8.57	2.55	0.16	0.45	8.57	2.55
Lithuania	0.13	0.55	6.87	2.64	0.15	0.54	6.87	2.64	0.19	0.54	6.86	2.64	0.26	0.54	6.86	2.64
Luxembourg	0.08	0.15	0.15	0.95	0.09	0.16	0.16	0.95	0.10	0.16	0.16	0.95	0.09	0.16	0.16	0.95
Montenegro																
Netherlands	3.63	2.75	2.62	3.42	3.64	2.74	2.61	3.40	3.52	2.70	2.58	3.37	3.67	2.74	2.62	3.41
N. Macedonia																
Norway	2.62	9.21	6.10	3.65	2.58	9.14	6.03	3.58	2.36	9.03	5.93	3.48	2.41	9.00	5.89	3.44
Poland	3.29	3.67	8.50	5.59	3.64	3.68	8.51	5.60	4.14	3.67	8.50	5.60	3.69	3.65	8.48	5.57
Portugal	1.16	1.55	1.04	1.83	1.06	1.54	1.03	1.82	1.07	1.53	1.01	1.81	1.28	1.54	1.02	1.82
Romania	0.87	2.12	1.54	3.12	0.95	2.12	1.53	3.12	1.05	2.11	1.53	3.12	1.06	2.12	1.53	3.12
Slovakia	0.34	0.53	0.50	2.09	0.35	0.53	0.50	2.09	0.40	0.53	0.50	2.09	0.40	0.53	0.50	2.09
Slovenia	0.18	0.31	0.21	1.00	0.17	0.31	0.21	1.00	0.16	0.31	0.21	1.00	0.18	0.31	0.21	1.00
Spain	6.12	6.72	5.28	6.07	6.05	6.66	5.21	6.01	6.16	6.63	5.19	5.98	5.64	6.69	5.25	6.04
Turkey	6.54	8.97	6.29	7.87	6.19	8.93	6.24	7.83	6.35	9.05	6.37	7.95	7.17	9.10	6.42	8.00
UK	22.66	12.63	8.93	9.73	23.59	12.99	9.29	10.08	24.33	13.49	9.79	10.58	21.46	13.00	9.30	10.10

Continued on next page

	2017				2018				2019				2020			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania	0.06	0.38	0.19	0.97	0.06	0.38	0.19	0.97	0.07	0.38	0.19	0.97	0.06	0.33	0.19	0.95
Belgium	1.71	1.65	1.63	2.41	1.70	1.66	1.64	2.42	1.66	1.67	1.65	2.43	1.74	1.69	1.67	2.43
Bulgaria	0.28	0.77	0.53	1.30	0.34	0.77	0.53	1.30	0.75	0.78	0.53	1.31	0.37	0.73	0.53	1.29
Croatia	0.35	2.37	0.34	1.12	0.33	2.37	0.34	1.12	0.34	2.37	0.34	1.12	0.32	2.37	0.34	1.09
Czechia	0.80	1.16	1.05	2.60	0.95	1.19	1.07	2.62	1.01	1.21	1.09	2.64	1.07	1.21	1.09	2.61
Denmark	1.45	3.06	0.98	2.53	1.60	3.06	0.98	2.53	1.56	3.06	0.97	2.52	1.60	3.10	1.01	2.53
Estonia	0.21	1.30	8.33	2.46	0.22	1.31	8.33	2.46	0.22	1.31	8.34	2.46	0.24	1.31	8.34	2.41
France	18.99	10.47	8.92	9.69	18.09	10.48	8.93	9.70	17.44	10.46	8.91	9.69	17.31	10.48	8.92	9.68
Germany	16.32	13.12	12.11	13.66	16.36	13.14	12.13	13.68	17.08	13.10	12.09	13.64	17.49	13.28	12.27	13.78
Greece	1.96	4.98	1.02	1.79	2.03	4.98	1.01	1.78	1.87	4.97	1.00	1.78	1.89	4.90	0.98	1.74
Hungary	0.66	1.02	0.85	2.40	0.57	1.03	0.86	2.41	0.76	1.04	0.87	2.42	0.91	1.04	0.86	2.38
Italy	10.21	9.84	7.35	8.12	10.00	9.80	7.30	8.08	9.18	9.67	7.18	7.95	10.80	9.55	7.05	7.80
Latvia	0.19	0.45	8.57	2.50	0.25	0.45	8.58	2.50	0.24	0.45	8.57	2.50	0.24	0.46	8.58	2.45
Lithuania	0.31	0.54	6.86	2.58	0.37	0.54	6.87	2.59	0.38	0.55	6.87	2.59	0.39	0.55	6.88	2.54
Luxembourg	0.12	0.16	0.16	0.94	0.13	0.16	0.16	0.94	0.13	0.16	0.16	0.94	0.14	0.18	0.18	0.93
Montenegro	0.03	0.26	0.05	0.82	0.03	0.27	0.05	0.82	0.03	0.27	0.05	0.82	0.03	0.26	0.04	0.80
Netherlands	3.70	2.77	2.64	3.42	3.91	2.81	2.68	3.45	4.18	2.84	2.71	3.49	4.29	2.90	2.77	3.53
N. Macedonia													0.05	0.21	0.13	0.89
Norway	2.65	8.99	5.92	3.41	2.65	9.00	5.94	3.43	2.62	8.96	5.90	3.39	2.37	8.93	5.84	3.28
Poland	3.81	3.70	8.53	5.57	4.24	3.74	8.57	5.61	4.10	3.77	8.60	5.64	4.50	3.79	8.63	5.61
Portugal	1.05	1.54	1.03	1.80	1.14	1.55	1.04	1.81	1.15	1.55	1.04	1.81	1.07	1.54	1.03	1.79
Romania	1.40	2.13	1.55	3.10	1.53	2.15	1.57	3.12	1.61	2.17	1.59	3.14	1.66	2.17	1.59	3.11
Slovakia	0.40	0.53	0.50	2.05	0.46	0.54	0.51	2.06	0.63	0.54	0.51	2.06	0.67	0.55	0.52	2.03
Slovenia	0.18	0.31	0.21	0.99	0.19	0.32	0.22	0.99	0.20	0.32	0.22	1.00	0.19	0.32	0.22	0.98
Spain	6.19	6.72	5.28	6.05	6.27	6.75	5.31	6.08	5.98	6.75	5.31	6.09	5.72	6.62	5.18	5.94
Turkey	6.88	9.03	6.35	7.90	6.92	8.82	6.14	7.70	7.11	8.87	6.19	7.74	5.73	8.86	6.18	7.70
UK	20.10	12.73	9.04	9.82	19.65	12.73	9.05	9.82	19.69	12.80	9.11	9.89	19.14	12.68	8.98	9.74

Continued on next page

	2021				2022			
	DB	ABS 1	ABS 2	ABS 3	DB	ABS 1	ABS 2	ABS 3
Albania	0.07	0.33	0.19	0.95	0.07	0.33	0.19	0.95
Belgium	1.88	1.69	1.67	2.42	2.12	1.69	1.68	2.43
Bulgaria	0.38	0.73	0.54	1.30	0.44	0.73	0.54	1.29
Croatia	0.41	2.37	0.34	1.10	0.40	2.37	0.34	1.10
Czechia	1.18	1.21	1.09	2.61	1.23	1.24	1.12	2.64
Denmark	1.59	3.11	1.02	2.53	1.69	3.11	1.02	2.53
Estonia	0.23	1.32	8.34	2.41	0.25	1.32	8.34	2.42
France	17.04	10.42	8.86	9.62	16.53	10.20	8.64	9.40
Germany	17.00	13.07	12.05	13.57	17.30	12.87	11.86	13.38
Greece	2.50	4.90	0.97	1.73	2.70	4.89	0.97	1.73
Hungary	0.72	1.04	0.86	2.38	1.00	1.03	0.85	2.37
Italy	10.90	9.55	7.05	7.81	10.69	9.45	6.95	7.71
Latvia	0.25	0.46	8.58	2.45	0.26	0.46	8.58	2.45
Lithuania	0.39	0.56	6.88	2.55	0.53	0.57	6.89	2.56
Luxembourg	0.12	0.18	0.18	0.94	0.16	0.18	0.18	0.93
Montenegro	0.03	0.27	0.05	0.80	0.03	0.27	0.05	0.80
Netherlands	4.33	2.90	2.77	3.53	4.20	2.92	2.79	3.55
N. Macedonia	0.06	0.20	0.13	0.89	0.07	0.20	0.13	0.89
Norway	2.54	9.07	5.99	3.42	2.68	9.24	6.15	3.59
Poland	4.60	3.74	8.58	5.56	4.73	3.75	8.58	5.57
Portugal	1.17	1.54	1.03	1.78	1.10	1.55	1.03	1.79
Romania	1.59	2.17	1.58	3.10	1.60	2.18	1.60	3.11
Slovakia	0.62	0.54	0.52	2.03	0.64	0.54	0.51	2.02
Slovenia	0.23	0.32	0.22	0.98	0.24	0.32	0.22	0.98
Spain	5.88	6.62	5.18	5.93	6.26	6.64	5.19	5.95
Turkey	4.68	8.91	6.23	7.75	3.32	9.10	6.42	7.94
UK	19.60	12.80	9.11	9.87	19.75	12.86	9.17	9.92

(*Notes.* The table presents defense burdens (measured as military expenditure over GDP) and alternative specifications of the Average Benefit Share (ABS) for NATO-Europe from 1993 to 2022. Each ABS combines GDP, population, and one threat-related component, weighted equally. ABS 1 is based on total exposed land borders; ABS 2 uses only borders exposed to Russia; and ABS 3 using a distance category. Defense burden and ABS values are normalized to sum to 100% across countries in each year.)

B.6 | The Concordance between Defense Burdens and Benefit Shares in NATO

In addition to section 3.5, we calculated the four average benefit share alternatives and applied the Wilcoxon signed-rank correlation tests to NATO as a whole. Table B.7 shows the defense burden and the four average benefit shares for all NATO members from 1995 to 2020 at five-year intervals, while Table B.10 provides the corresponding annual data from 1993 to 2022. The respective figures for the European countries appear much lower compared to Table B.4 and Table B.6, since the US and Canada bear a large share of the total defense burden and the total benefits. This also shifts the number of over- and undercontributors significantly, especially since the US bears a disproportionately high defense burden share of 65.51% in 2000, 70.64% in 2010, and 70.36% in 2020, and receives a benefit share of only 31.67% in 2000, 28.63% in 2010, and 31.45% in 2020, according to the average benefit share with EBs also used by Sandler and Shimizu (2014). In fact, only the US and the UK are overcontributors over the whole period, and France is an overcontributor from 1995 to 2005. This is consistent with the findings of Sandler and Shimizu (2014), although our data are slightly different and we did not include counterterrorism benefits. The other average benefit measures may not be representative of NATO as a whole, as they focus on the thread imposed by Russia, which mainly affects European countries.

Table B.7 shows the defense burden and the four average benefit shares for all NATO members from 1995 to 2020 at five-year intervals

Table B.8 shows the same Wilcoxon signed-rank correlation tests as in Section 3.5 applied to the whole of NATO. For the average benefit share with an exposed border, we can reject the null hypothesis at a significance level of 0.05 or lower from 2000 onwards and at a significance level of 0.01 from 2004 onwards. This differs slightly from the results of Sandler and Shimizu (2014), as we also find evidence of free riding in the period 1999-2002, but is mainly consistent, especially for the period after 2004, where we find strong evidence of free riding in NATO. Therefore, we conclude that there is persistent free riding within NATO, mainly due to the large overcontribution of the US.

Table B.7: Defense burden (DB) and Average Benefit Shares 1-4 in NATO for selected years (1995, 2000, 2005, 2010, 2015, 2020)

	1995					2000					2005				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania															
Belgium	0.92	1.05	1.04	2.71	1.60	0.65	0.84	0.83	2.07	1.25	0.54	0.86	0.86	1.65	1.12
Bulgaria											0.08	0.42	0.33	1.12	0.62
Canada	1.90	23.36	2.56	4.23	10.05	1.70	23.12	2.56	3.79	9.82	1.65	22.75	2.62	3.42	9.59
Croatia															
Czechia						0.24	0.60	0.54	3.01	1.38	0.31	0.59	0.55	2.14	1.10
Denmark	0.65	1.36	0.61	3.94	1.97	0.49	1.25	0.50	2.97	1.57	0.44	1.25	0.52	2.11	1.29
Estonia											0.03	0.48	8.27	2.45	3.73
France	8.31	6.47	5.91	7.58	6.65	5.81	5.43	4.88	6.11	5.47	5.64	5.55	5.01	5.81	5.46
Germany	8.02	9.38	8.90	12.23	10.17	5.42	7.17	6.80	9.27	7.75	3.85	6.93	6.58	8.17	7.23
Greece	0.87	2.26	0.76	2.43	1.82	0.93	2.15	0.67	1.90	1.57	0.89	2.11	0.71	1.50	1.44
Hungary						0.15	0.72	0.51	2.98	1.40	0.20	0.62	0.52	2.11	1.08
Italy	3.56	5.89	4.97	6.64	5.83	4.07	5.26	4.35	5.59	5.07	3.78	5.30	4.43	5.22	4.98
Latvia											0.03	0.20	8.51	2.49	3.73
Lithuania											0.04	0.26	6.76	2.54	3.19
Luxembourg	0.03	0.06	0.06	1.73	0.62	0.02	0.05	0.05	1.29	0.47	0.03	0.06	0.06	0.86	0.33
Montenegro															
Netherlands	1.66	1.66	1.61	3.28	2.18	1.22	1.43	1.38	2.62	1.81	1.21	1.48	1.44	2.23	1.72
N. Macedonia															
Norway	0.73	3.35	33.83	5.50	14.23	0.60	3.30	16.40	4.18	7.96	0.62	3.30	5.38	2.92	3.87
Poland						0.64	2.13	19.32	5.60	9.02	0.75	1.99	7.12	4.21	4.44
Portugal	0.42	0.89	0.70	2.37	1.32	0.34	0.82	0.63	1.87	1.11	0.40	0.82	0.64	1.43	0.96
Romania											0.25	1.14	0.94	2.52	1.53
Slovakia											0.10	0.29	0.28	1.87	0.81
Slovenia											0.07	0.21	0.12	0.91	0.42
Spain	2.37	3.59	3.07	4.73	3.80	2.10	3.24	2.72	3.96	3.31	2.03	3.54	3.04	3.83	3.47
Turkey	1.37	4.19	3.20	6.53	4.64	2.05	4.19	3.21	5.68	4.36	1.53	4.20	3.27	4.85	4.11
UK	7.93	6.68	5.35	7.02	6.35	8.05	6.63	5.31	6.55	6.16	7.83	6.61	5.32	6.11	6.01
United States	61.27	29.80	27.43	29.09	28.77	65.51	31.67	29.32	30.56	30.52	67.69	29.02	26.72	27.52	27.75

Continued on next page

	2010					2015					2020				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania	0.02	0.20	0.12	0.88	0.40	0.01	0.20	0.11	0.87	0.39	0.02	0.16	0.11	0.84	0.37
Belgium	0.50	0.89	0.88	1.64	1.14	0.47	0.84	0.83	1.59	1.09	0.48	0.85	0.84	1.57	1.08
Bulgaria	0.08	0.41	0.32	1.08	0.60	0.07	0.39	0.31	1.06	0.59	0.10	0.37	0.30	1.03	0.57
Canada	1.85	22.59	2.86	3.62	9.69	2.00	22.45	2.72	3.48	9.55	2.09	22.41	2.70	3.42	9.51
Croatia	0.09	0.91	0.22	0.98	0.70	0.10	0.89	0.20	0.95	0.68	0.09	0.88	0.19	0.91	0.66
Czechia	0.24	0.64	0.60	2.11	1.12	0.20	0.59	0.56	2.07	1.07	0.29	0.62	0.58	2.03	1.08
Denmark	0.43	1.24	0.53	2.04	1.27	0.37	1.20	0.48	2.00	1.23	0.44	1.21	0.50	1.95	1.22
Estonia	0.03	0.47	8.27	2.34	3.69	0.05	0.47	8.27	2.34	3.69	0.06	0.47	8.27	2.25	3.66
France	4.98	5.56	5.03	5.79	5.46	5.08	5.18	4.65	5.41	5.08	4.77	5.08	4.55	5.28	4.97
Germany	4.12	6.81	6.47	7.98	7.09	4.25	6.45	6.10	7.62	6.72	4.82	6.51	6.16	7.61	6.76
Greece	0.78	2.06	0.71	1.46	1.41	0.54	1.93	0.57	1.33	1.28	0.52	1.87	0.53	1.26	1.22
Hungary	0.13	0.56	0.50	2.02	1.03	0.13	0.53	0.47	1.99	1.00	0.25	0.53	0.47	1.92	0.98
Italy	3.07	5.18	4.32	5.08	4.86	2.47	4.75	3.89	4.65	4.43	2.98	4.51	3.66	4.38	4.18
Latvia	0.02	0.20	8.50	2.37	3.69	0.03	0.19	8.50	2.37	3.69	0.07	0.19	8.50	2.27	3.65
Lithuania	0.03	0.25	6.76	2.42	3.14	0.05	0.24	6.75	2.42	3.14	0.11	0.24	6.75	2.32	3.10
Luxembourg	0.02	0.07	0.07	0.83	0.33	0.03	0.08	0.08	0.83	0.33	0.04	0.08	0.08	0.81	0.32
Montenegro											0.01	0.10	0.03	0.75	0.29
Netherlands	1.07	1.50	1.46	2.22	1.73	0.96	1.37	1.33	2.08	1.59	1.18	1.42	1.38	2.10	1.64
N. Macedonia											0.01	0.10	0.08	0.80	0.33
Norway	0.62	3.31	5.44	2.88	3.88	0.65	3.25	5.38	2.82	3.82	0.65	3.19	5.33	2.67	3.73
Poland	0.84	2.04	7.17	4.16	4.46	1.14	1.97	7.10	4.09	4.39	1.24	1.99	7.12	4.01	4.37
Portugal	0.34	0.80	0.63	1.39	0.94	0.29	0.73	0.56	1.32	0.87	0.30	0.73	0.55	1.28	0.85
Romania	0.20	1.12	0.92	2.43	1.49	0.29	1.08	0.88	2.40	1.45	0.46	1.08	0.89	2.33	1.43
Slovakia	0.11	0.30	0.29	1.81	0.80	0.11	0.29	0.28	1.79	0.79	0.19	0.29	0.28	1.73	0.77
Slovenia	0.07	0.16	0.12	0.88	0.39	0.04	0.15	0.11	0.87	0.38	0.05	0.15	0.12	0.84	0.37
Spain	1.89	3.63	3.14	3.90	3.56	1.69	3.28	2.79	3.55	3.20	1.58	3.22	2.73	3.45	3.13
Turkey	1.69	4.40	3.48	5.00	4.29	1.74	4.54	3.62	5.14	4.43	1.58	4.44	3.53	4.98	4.32
UK	6.12	6.05	4.79	5.55	5.46	6.68	6.31	5.05	5.80	5.72	5.27	5.84	4.58	5.30	5.24
United States	70.64	28.63	26.38	27.14	27.39	70.56	30.67	28.42	29.17	29.42	70.36	31.45	29.20	29.93	30.19

(*Notes.* The table presents Defense burdens (measured as military expenditure over GDP) and alternative specifications of the Average Benefit Share (ABS) for NATO for selected years (1995, 2000, 2005, 2010, 2015, 2020) to illustrate changes over time. Each ABS combines GDP, population, and one threat-related component, weighted equally. ABS 1 is based on total exposed land borders; ABS 2 uses only borders exposed to Russia; and ABS 3 using a distance category; ABS 4 uses weighted composite of GDP, population size, and including three threat dimensions: exposed land borders, exposed borders with Russia, and a distance category. DB and ABS values are normalized to sum to 100% across countries in each year.)

Table B.8: Wilcoxon signed-rank correlation of ME/NATO ME and alternative Average Benefit Shares

		Average Benefit Share 1	Average Benefit Share 2	Average Benefit Share 3	Average Benefit Share 4
Year	Size	R (p)	R (p)	R (p)	R (p)
1993	15	28* (0.07)	38 (0.23)	17** (0.01)	26* (0.06)
1994	15	29* (0.08)	39 (0.25)	18** (0.02)	30* (0.09)
1995	15	33 (0.14)	49 (0.56)	18** (0.02)	32 (0.12)
1996	15	36 (0.19)	49 (0.56)	18** (0.02)	34 (0.15)
1997	15	31 (0.11)	46 (0.45)	18** (0.02)	31 (0.11)
1998	15	32 (0.12)	47 (0.49)	19** (0.02)	31 (0.11)
1999	18	43* (0.07)	59 (0.26)	28** (0.01)	41* (0.05)
2000	18	35** (0.03)	50 (0.13)	24*** (0.01)	31** (0.02)
2001	18	33** (0.02)	50 (0.13)	24*** (0.01)	31** (0.02)
2002	18	27*** (0.01)	46* (0.09)	22*** (0.00)	30** (0.01)
2003	18	29*** (0.01)	45* (0.08)	22*** (0.00)	31** (0.02)
2004	25	55*** (0.00)	62*** (0.01)	42*** (0.00)	44*** (0.00)
2005	25	43*** (0.00)	60*** (0.00)	36*** (0.00)	42*** (0.00)
2006	25	41*** (0.00)	61*** (0.01)	35*** (0.00)	42*** (0.00)
2007	25	45*** (0.00)	62*** (0.01)	41*** (0.00)	42*** (0.00)
2008	25	41*** (0.00)	65*** (0.01)	34*** (0.00)	41*** (0.00)
2009	27	35*** (0.00)	69*** (0.00)	30*** (0.00)	39*** (0.00)
2010	27	29*** (0.00)	50*** (0.00)	28*** (0.00)	38*** (0.00)
2011	27	30*** (0.00)	46*** (0.00)	28*** (0.00)	39*** (0.00)
2012	27	34*** (0.00)	46*** (0.00)	28*** (0.00)	39*** (0.00)
2013	27	37*** (0.00)	57*** (0.00)	34*** (0.00)	42*** (0.00)
2014	27	45*** (0.00)	63*** (0.00)	38*** (0.00)	44*** (0.00)
2015	27	37*** (0.00)	60*** (0.00)	34*** (0.00)	43*** (0.00)
2016	27	29*** (0.00)	59*** (0.00)	29*** (0.00)	33*** (0.00)
2017	28	32*** (0.00)	63*** (0.00)	30*** (0.00)	31*** (0.00)
2018	28	29*** (0.00)	65*** (0.00)	29*** (0.00)	31*** (0.00)
2019	28	28*** (0.00)	57*** (0.00)	29*** (0.00)	29*** (0.00)
2020	29	29*** (0.00)	61*** (0.00)	29*** (0.00)	30*** (0.00)
2021	29	29*** (0.00)	75*** (0.00)	30*** (0.00)	31*** (0.00)
2022	29	29*** (0.00)	69*** (0.00)	30*** (0.00)	30*** (0.00)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. The construction of Average Benefit Shares are explained in the first paragraph of 3.5.1. In parentheses are prob-values, indicating the probability of a type I error.
***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

Table B.9: Wilcoxon signed-rank correlation of ME/NATO ME and single benefit shares

		GDP	POP	EB	EBR	DC
Year	Size	R (p)	R (p)	R (p)	R (p)	R (p)
1993	15	26* (0.06)	16** (0.01)	55 (0.80)	15*** (0.01)	20** (0.02)
1994	15	27* (0.06)	17** (0.01)	54 (0.76)	15*** (0.01)	22** (0.03)
1995	15	24** (0.04)	19** (0.02)	54 (0.76)	15*** (0.01)	25** (0.05)
1996	15	27* (0.06)	19** (0.02)	52 (0.68)	15*** (0.01)	25** (0.05)
1997	15	24** (0.04)	21** (0.03)	52 (0.68)	15*** (0.01)	23** (0.04)
1998	15	26* (0.06)	24** (0.04)	51 (0.64)	15*** (0.01)	24** (0.04)
1999	18	38** (0.04)	30** (0.01)	75 (0.67)	33** (0.02)	38** (0.04)
2000	18	36** (0.03)	25*** (0.01)	77 (0.73)	33** (0.02)	35** (0.03)
2001	18	32** (0.02)	25*** (0.01)	76 (0.70)	33** (0.02)	33** (0.02)
2002	18	31** (0.02)	25*** (0.01)	77 (0.73)	33** (0.02)	32** (0.02)
2003	18	23*** (0.00)	24*** (0.01)	79 (0.80)	33** (0.02)	33** (0.02)
2004	25	25*** (0.00)	43*** (0.00)	153 (0.81)	110 (0.16)	64*** (0.01)
2005	25	29*** (0.00)	41*** (0.00)	160 (0.96)	110 (0.16)	62*** (0.01)
2006	25	27*** (0.00)	39*** (0.00)	151 (0.77)	110 (0.16)	61*** (0.01)
2007	25	26*** (0.00)	44*** (0.00)	157 (0.89)	110 (0.16)	62*** (0.01)
2008	25	29*** (0.00)	36*** (0.00)	157 (0.89)	110 (0.16)	63*** (0.01)
2009	27	31*** (0.00)	29*** (0.00)	163 (0.55)	120 (0.10)	62*** (0.00)
2010	27	27*** (0.00)	29*** (0.00)	173 (0.71)	120 (0.10)	61*** (0.00)
2011	27	27*** (0.00)	30*** (0.00)	173 (0.71)	120 (0.10)	61*** (0.00)
2012	27	27*** (0.00)	30*** (0.00)	171 (0.68)	120 (0.10)	61*** (0.00)
2013	27	27*** (0.00)	33*** (0.00)	174 (0.73)	120 (0.10)	63*** (0.00)
2014	27	27*** (0.00)	35*** (0.00)	176 (0.77)	120 (0.10)	68*** (0.00)
2015	27	27*** (0.00)	29*** (0.00)	156 (0.44)	120 (0.10)	62*** (0.00)
2016	27	30*** (0.00)	30*** (0.00)	165 (0.58)	120 (0.10)	61*** (0.00)
2017	28	33*** (0.00)	34*** (0.00)	186 (0.71)	125* (0.08)	68*** (0.00)
2018	28	45*** (0.00)	36*** (0.00)	187 (0.73)	125* (0.08)	68*** (0.00)
2019	28	49*** (0.00)	33*** (0.00)	173 (0.51)	125* (0.08)	66*** (0.00)
2020	29	36*** (0.00)	33*** (0.00)	196 (0.65)	130* (0.06)	69*** (0.00)
2021	29	45*** (0.00)	34*** (0.00)	203 (0.77)	130* (0.06)	72*** (0.00)
2022	29	45*** (0.00)	34*** (0.00)	200 (0.72)	130* (0.06)	68*** (0.00)

(*Notes.* Numbers in parentheses are prob-values indicating the probability of a type I error when testing the null hypothesis of no association between ME/GDP and GDP ranks. ***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004-2008; are 89 at .05 level and 68 at .01 level for 2009-2016; are 98 at .05 level and 75 at .01 level for 2017-2019; are 107 at .05 level and 83 at .01 level for 2020-2022. Iceland is excluded for all years.)

Table B.10: Defense burden (DB) and Average Benefit Share (ABS) alternatives in NATO from 1993 to 2022

	1993					1994					1995				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania															
Belgium	0.76	1.00	0.99	2.66	1.55	0.82	1.01	1.01	2.67	1.56	0.92	1.05	1.04	2.71	1.60
Bulgaria															
Canada	2.08	23.49	2.68	4.35	10.17	1.98	23.43	2.62	4.29	10.11	1.90	23.36	2.56	4.23	10.05
Croatia															
Czechia															
Denmark	0.54	1.33	0.57	3.91	1.93	0.56	1.34	0.58	3.92	1.94	0.65	1.36	0.61	3.94	1.97
Estonia															
France	7.26	6.36	5.80	7.47	6.54	7.71	6.35	5.79	7.46	6.53	8.31	6.47	5.91	7.58	6.65
Germany	7.10	9.07	8.58	11.92	9.86	7.07	9.11	8.62	11.95	9.89	8.02	9.38	8.90	12.23	10.17
Greece	0.68	2.25	0.74	2.41	1.80	0.74	2.25	0.75	2.41	1.80	0.87	2.26	0.76	2.43	1.82
Hungary															
Italy	3.70	6.05	5.13	6.80	6.00	3.73	5.98	5.06	6.73	5.93	3.56	5.89	4.97	6.64	5.83
Latvia															
Lithuania															
Luxembourg	0.02	0.06	0.06	1.72	0.61	0.02	0.06	0.06	1.72	0.61	0.03	0.06	0.06	1.73	0.62
Montenegro															
Netherlands	1.43	1.58	1.53	3.20	2.10	1.48	1.59	1.55	3.21	2.12	1.66	1.66	1.61	3.28	2.18
N. Macedonia															
Norway	0.64	3.33	33.81	5.48	14.21	0.70	3.33	33.81	5.48	14.21	0.73	3.35	33.83	5.50	14.23
Poland															
Portugal	0.34	0.88	0.69	2.36	1.31	0.34	0.87	0.69	2.35	1.31	0.42	0.89	0.70	2.37	1.32
Romania															
Slovakia															
Slovenia															
Spain	2.04	3.59	3.07	4.74	3.80	2.09	3.53	3.01	4.68	3.74	2.37	3.59	3.07	4.73	3.80
Turkey	1.43	4.22	3.23	6.56	4.67	1.09	4.12	3.13	6.46	4.57	1.37	4.19	3.20	6.53	4.64
UK	7.73	6.49	5.16	6.83	6.16	7.97	6.52	5.19	6.86	6.19	7.93	6.68	5.35	7.02	6.35
United States	64.24	30.32	27.95	29.61	29.29	63.69	30.51	28.13	29.80	29.48	61.27	29.80	27.43	29.09	28.77

Continued on next page

	1996					1997					1998				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania															
Belgium	0.89	1.01	1.00	2.67	1.56	0.79	0.95	0.95	2.61	1.50	0.78	0.94	0.93	2.60	1.49
Bulgaria															
Canada	1.81	23.37	2.57	4.23	10.06	1.70	23.42	2.61	4.28	10.10	1.66	23.33	2.53	4.19	10.02
Croatia															
Czechia															
Denmark	0.65	1.35	0.60	3.93	1.96	0.60	1.32	0.57	3.90	1.93	0.61	1.31	0.56	3.89	1.92
Estonia															
France	8.19	6.36	5.79	7.46	6.54	7.42	6.06	5.50	7.16	6.24	7.18	6.02	5.46	7.12	6.20
Germany	7.71	9.02	8.54	11.87	9.81	6.68	8.45	7.96	11.30	9.24	6.66	8.29	7.81	11.14	9.08
Greece	0.97	2.27	0.76	2.43	1.82	0.98	2.26	0.75	2.42	1.81	1.03	2.25	0.74	2.41	1.80
Hungary															
Italy	4.37	6.05	5.13	6.79	5.99	4.31	5.89	4.97	6.64	5.84	4.45	5.82	4.90	6.57	5.77
Latvia															
Lithuania															
Luxembourg	0.03	0.06	0.06	1.73	0.61	0.03	0.06	0.06	1.72	0.61	0.03	0.06	0.06	1.72	0.61
Montenegro															
Netherlands	1.65	1.62	1.57	3.24	2.14	1.46	1.55	1.51	3.17	2.08	1.46	1.56	1.51	3.18	2.08
N. Macedonia															
Norway	0.74	3.37	33.85	5.51	14.24	0.70	3.36	33.84	5.51	14.24	0.71	3.33	33.81	5.48	14.21
Poland															
Portugal	0.41	0.89	0.70	2.37	1.32	0.39	0.87	0.69	2.35	1.31	0.38	0.87	0.69	2.36	1.31
Romania															
Slovakia															
Slovenia															
Spain	2.37	3.59	3.07	4.74	3.80	2.11	3.48	2.96	4.63	3.69	2.21	3.48	2.96	4.63	3.69
Turkey	1.58	4.22	3.23	6.57	4.67	1.67	4.26	3.27	6.60	4.71	1.88	4.42	3.43	6.76	4.87
UK	8.11	6.71	5.38	7.05	6.38	8.53	6.96	5.63	7.30	6.63	8.81	6.99	5.66	7.33	6.66
United States	60.52	30.13	27.75	29.42	29.10	62.66	31.10	28.73	30.39	30.08	62.16	31.33	28.95	30.62	30.30

Continued on next page

	1999					2000					2001				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania															
Belgium	0.75	0.88	0.87	2.11	1.29	0.65	0.84	0.83	2.07	1.25	0.61	0.83	0.83	2.06	1.24
Bulgaria															
Canada	1.71	22.93	2.45	3.68	9.69	1.70	23.12	2.56	3.79	9.82	1.68	23.09	2.53	3.77	9.80
Croatia															
Czechia	0.25	0.61	0.55	3.02	1.39	0.24	0.60	0.54	3.01	1.38	0.24	0.61	0.54	3.01	1.38
Denmark	0.58	1.27	0.53	3.00	1.60	0.49	1.25	0.50	2.97	1.57	0.51	1.24	0.50	2.97	1.57
Estonia															
France	6.79	5.65	5.10	6.34	5.70	5.81	5.43	4.88	6.11	5.47	5.62	5.41	4.85	6.09	5.45
Germany	6.38	7.74	7.26	9.73	8.24	5.42	7.17	6.80	9.27	7.75	5.19	7.09	6.73	9.20	7.67
Greece	1.04	2.17	0.69	1.92	1.59	0.93	2.15	0.67	1.90	1.57	0.89	2.16	0.67	1.91	1.58
Hungary	0.15	0.73	0.52	2.99	1.41	0.15	0.72	0.51	2.98	1.40	0.17	0.73	0.51	2.98	1.41
Italy	4.37	5.46	4.55	5.79	5.27	4.07	5.26	4.35	5.59	5.07	3.93	5.25	4.34	5.57	5.05
Latvia															
Lithuania															
Luxembourg	0.03	0.06	0.06	1.29	0.47	0.02	0.05	0.05	1.29	0.47	0.03	0.05	0.05	1.29	0.47
Montenegro															
Netherlands	1.46	1.48	1.43	2.67	1.86	1.22	1.43	1.38	2.62	1.81	1.25	1.44	1.39	2.63	1.82
N. Macedonia															
Norway	0.69	3.28	16.38	4.17	7.94	0.60	3.30	16.40	4.18	7.96	0.60	3.30	16.40	4.18	7.96
Poland	0.67	2.15	19.34	5.63	9.04	0.64	2.13	19.32	5.60	9.02	0.73	2.14	19.33	5.62	9.03
Portugal	0.38	0.83	0.65	1.88	1.12	0.34	0.82	0.63	1.87	1.11	0.35	0.82	0.64	1.87	1.11
Romania															
Slovakia															
Slovenia															
Spain	2.31	3.30	2.79	4.03	3.37	2.10	3.24	2.72	3.96	3.31	2.06	3.27	2.75	3.99	3.34
Turkey	2.07	4.14	3.17	5.64	4.32	2.05	4.19	3.21	5.68	4.36	1.45	4.08	3.10	5.57	4.25
UK	8.47	6.68	5.37	6.60	6.22	8.05	6.63	5.31	6.55	6.16	7.95	6.54	5.23	6.46	6.08
United States	61.93	30.62	28.28	29.52	29.48	65.51	31.67	29.32	30.56	30.52	66.74	31.95	29.60	30.84	30.80

Continued on next page

	2002					2003					2004				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania															
Belgium	0.56	0.84	0.84	2.07	1.25	0.59	0.88	0.87	2.11	1.29	0.57	0.87	0.87	1.66	1.13
Bulgaria											0.08	0.42	0.33	1.13	0.62
Canada	1.52	23.06	2.50	3.74	9.77	1.51	23.12	2.56	3.79	9.82	1.52	22.47	2.52	3.32	9.44
Croatia															
Czechia	0.27	0.62	0.55	3.02	1.40	0.29	0.63	0.56	3.03	1.41	0.27	0.61	0.55	2.13	1.10
Denmark	0.48	1.25	0.51	2.97	1.58	0.49	1.27	0.53	3.00	1.60	0.48	1.25	0.52	2.11	1.29
Estonia											0.03	0.47	8.27	2.45	3.73
France	5.46	5.47	4.92	6.16	5.52	5.85	5.69	5.14	6.37	5.73	5.98	5.61	5.07	5.86	5.51
Germany	4.93	7.10	6.74	9.21	7.69	5.00	7.32	6.96	9.42	7.90	4.80	7.12	6.77	8.35	7.41
Greece	0.85	2.17	0.69	1.92	1.60	0.76	2.21	0.73	1.96	1.63	0.84	2.16	0.72	1.51	1.46
Hungary	0.19	0.74	0.53	3.00	1.42	0.21	0.75	0.54	3.01	1.43	0.21	0.73	0.52	2.11	1.12
Italy	3.86	5.30	4.39	5.63	5.11	4.07	5.49	4.58	5.82	5.30	4.06	5.39	4.50	5.30	5.06
Latvia											0.03	0.20	8.51	2.49	3.73
Lithuania											0.04	0.26	6.77	2.54	3.19
Luxembourg	0.02	0.06	0.06	1.29	0.47	0.03	0.06	0.06	1.29	0.47	0.03	0.06	0.06	0.86	0.33
Montenegro															
Netherlands	1.20	1.47	1.42	2.66	1.85	1.27	1.53	1.49	2.72	1.91	1.26	1.50	1.46	2.25	1.74
N. Macedonia															
Norway	0.73	3.32	16.41	4.20	7.98	0.69	3.33	16.43	4.21	7.99	0.66	3.25	5.34	2.89	3.83
Poland	0.67	2.13	19.32	5.60	9.02	0.63	2.11	19.30	5.58	8.99	0.64	2.02	7.09	4.18	4.43
Portugal	0.35	0.83	0.64	1.88	1.12	0.36	0.84	0.66	1.90	1.13	0.38	0.82	0.64	1.44	0.97
Romania											0.21	1.13	0.93	2.51	1.52
Slovakia											0.10	0.29	0.28	1.87	0.81
Slovenia											0.07	0.21	0.12	0.91	0.42
Spain	1.83	3.35	2.84	4.07	3.42	1.95	3.52	3.01	4.25	3.59	2.05	3.50	3.00	3.80	3.43
Turkey	1.62	4.13	3.16	5.63	4.31	1.56	4.21	3.23	5.70	4.38	1.47	4.12	3.17	4.76	4.02
UK	7.90	6.60	5.28	6.52	6.13	7.94	6.65	5.34	6.57	6.19	8.09	6.63	5.35	6.15	6.04
United States	67.56	31.55	29.20	30.44	30.40	66.81	30.38	28.03	29.26	29.22	66.16	28.91	26.63	27.43	27.66

Continued on next page

	2005					2006					2007				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania															
Belgium	0.54	0.86	0.86	1.65	1.12	0.52	0.86	0.85	1.65	1.12	0.58	0.88	0.87	1.67	1.14
Bulgaria	0.08	0.42	0.33	1.12	0.62	0.09	0.41	0.33	1.12	0.62	0.11	0.42	0.33	1.13	0.62
Canada	1.65	22.75	2.62	3.42	9.59	1.79	22.65	2.70	3.49	9.62	1.94	22.67	2.72	3.51	9.63
Croatia															
Czechia	0.31	0.59	0.55	2.14	1.10	0.30	0.63	0.56	2.15	1.11	0.30	0.65	0.58	2.17	1.13
Denmark	0.44	1.25	0.52	2.11	1.29	0.47	1.24	0.52	2.11	1.29	0.47	1.25	0.53	2.11	1.30
Estonia	0.03	0.48	8.27	2.45	3.73	0.03	0.48	8.27	2.45	3.73	0.04	0.48	8.27	2.45	3.74
France	5.64	5.55	5.01	5.81	5.46	5.52	5.53	4.99	5.78	5.43	5.65	5.62	5.09	5.88	5.53
Germany	3.85	6.93	6.58	8.17	7.23	4.33	6.86	6.51	8.10	7.16	4.47	6.96	6.61	8.19	7.25
Greece	0.89	2.11	0.71	1.50	1.44	0.92	2.16	0.72	1.51	1.46	0.95	2.17	0.73	1.53	1.48
Hungary	0.20	0.62	0.52	2.11	1.08	0.17	0.72	0.51	2.10	1.11	0.20	0.73	0.52	2.11	1.12
Italy	3.78	5.30	4.43	5.22	4.98	3.57	5.27	4.38	5.18	4.94	3.57	5.33	4.44	5.23	5.00
Latvia	0.03	0.20	8.51	2.49	3.73	0.04	0.21	8.51	2.49	3.73	0.05	0.21	8.52	2.49	3.74
Lithuania	0.04	0.26	6.76	2.54	3.19	0.04	0.26	6.76	2.54	3.19	0.05	0.26	6.77	2.54	3.19
Luxembourg	0.03	0.06	0.06	0.86	0.33	0.03	0.07	0.07	0.86	0.33	0.03	0.07	0.07	0.86	0.33
Montenegro															
Netherlands	1.21	1.48	1.44	2.23	1.72	1.23	1.48	1.44	2.23	1.72	1.28	1.52	1.47	2.27	1.75
N. Macedonia															
Norway	0.62	3.30	5.38	2.92	3.87	0.60	3.30	5.40	2.94	3.88	0.66	3.32	5.42	2.96	3.90
Poland	0.75	1.99	7.12	4.21	4.44	0.80	2.06	7.13	4.22	4.47	0.96	2.10	7.17	4.26	4.51
Portugal	0.40	0.82	0.64	1.43	0.96	0.38	0.81	0.63	1.43	0.96	0.37	0.82	0.64	1.43	0.96
Romania	0.25	1.14	0.94	2.52	1.53	0.27	1.15	0.95	2.53	1.54	0.29	1.17	0.97	2.56	1.57
Slovakia	0.10	0.29	0.28	1.87	0.81	0.11	0.29	0.28	1.87	0.82	0.13	0.30	0.29	1.88	0.82
Slovenia	0.07	0.21	0.12	0.91	0.42	0.07	0.21	0.12	0.91	0.42	0.08	0.22	0.12	0.92	0.42
Spain	2.03	3.54	3.04	3.83	3.47	2.08	3.59	3.09	3.88	3.52	2.24	3.69	3.19	3.99	3.63
Turkey	1.53	4.20	3.27	4.85	4.11	1.57	4.24	3.30	4.88	4.14	1.67	4.30	3.35	4.94	4.19
UK	7.83	6.61	5.32	6.11	6.01	7.74	6.59	5.32	6.11	6.00	8.19	6.69	5.42	6.21	6.11
United States	67.69	29.02	26.72	27.52	27.75	67.33	28.93	26.65	27.45	27.68	65.74	28.18	25.90	26.70	26.93

Continued on next page

	2008					2009					2010				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania						0.02	0.20	0.12	0.88	0.40	0.02	0.20	0.12	0.88	0.40
Belgium	0.63	0.90	0.89	1.69	1.16	0.55	0.90	0.90	1.65	1.15	0.50	0.89	0.88	1.64	1.14
Bulgaria	0.12	0.42	0.33	1.13	0.63	0.09	0.41	0.33	1.09	0.61	0.08	0.41	0.32	1.08	0.60
Canada	1.95	22.67	2.73	3.52	9.64	1.85	22.14	2.65	3.41	9.40	1.85	22.59	2.86	3.62	9.69
Croatia						0.11	0.91	0.22	0.98	0.71	0.09	0.91	0.22	0.98	0.70
Czechia	0.29	0.68	0.62	2.20	1.17	0.27	0.66	0.60	2.11	1.13	0.24	0.64	0.60	2.11	1.12
Denmark	0.48	1.27	0.54	2.13	1.31	0.42	1.24	0.53	2.05	1.27	0.43	1.24	0.53	2.04	1.27
Estonia	0.04	0.48	8.27	2.45	3.74	0.03	0.47	8.27	2.34	3.69	0.03	0.47	8.27	2.34	3.69
France	5.58	5.74	5.20	6.00	5.65	5.52	5.68	5.16	5.91	5.58	4.98	5.56	5.03	5.79	5.46
Germany	4.55	7.06	6.71	8.29	7.35	4.35	6.93	6.59	8.10	7.21	4.12	6.81	6.47	7.98	7.09
Greece	1.07	2.19	0.75	1.54	1.50	1.04	2.15	0.75	1.50	1.47	0.78	2.06	0.71	1.46	1.41
Hungary	0.19	0.74	0.53	2.12	1.13	0.14	0.71	0.51	2.02	1.08	0.13	0.56	0.50	2.02	1.03
Italy	3.71	5.40	4.51	5.30	5.07	3.33	5.31	4.45	5.21	4.99	3.07	5.18	4.32	5.08	4.86
Latvia	0.06	0.21	8.52	2.50	3.74	0.04	0.20	8.51	2.38	3.70	0.02	0.20	8.50	2.37	3.69
Lithuania	0.05	0.26	6.77	2.55	3.19	0.04	0.25	6.76	2.43	3.15	0.03	0.25	6.76	2.42	3.14
Luxembourg	0.02	0.07	0.07	0.87	0.34	0.02	0.07	0.07	0.83	0.33	0.02	0.07	0.07	0.83	0.33
Montenegro															
Netherlands	1.25	1.57	1.53	2.32	1.81	1.19	1.55	1.51	2.27	1.78	1.07	1.50	1.46	2.22	1.73
N. Macedonia															
Norway	0.64	3.36	5.45	3.00	3.94	0.61	3.25	5.41	2.85	3.83	0.62	3.31	5.44	2.88	3.88
Poland	0.94	2.17	7.24	4.33	4.58	0.77	2.09	7.16	4.14	4.46	0.84	2.04	7.17	4.16	4.46
Portugal	0.37	0.83	0.65	1.44	0.97	0.37	0.82	0.64	1.40	0.95	0.34	0.80	0.63	1.39	0.94
Romania	0.30	1.18	0.98	2.57	1.58	0.22	1.13	0.94	2.45	1.51	0.20	1.12	0.92	2.43	1.49
Slovakia	0.14	0.31	0.30	1.89	0.83	0.13	0.30	0.29	1.81	0.80	0.11	0.30	0.29	1.81	0.80
Slovenia	0.08	0.22	0.13	0.92	0.42	0.08	0.22	0.13	0.88	0.41	0.07	0.16	0.12	0.88	0.39
Spain	2.24	3.78	3.28	4.08	3.72	1.97	3.74	3.25	4.01	3.66	1.89	3.63	3.14	3.90	3.56
Turkey	1.69	4.36	3.41	5.00	4.26	1.57	4.27	3.34	4.86	4.16	1.69	4.40	3.48	5.00	4.29
UK	7.35	6.38	5.11	5.90	5.80	6.26	6.02	4.77	5.53	5.44	6.12	6.05	4.79	5.55	5.46
United States	66.22	27.74	25.47	26.26	26.49	69.02	28.37	26.15	26.90	27.14	70.64	28.63	26.38	27.14	27.39

Continued on next page

	2011					2012					2013				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania	0.02	0.20	0.12	0.88	0.40	0.02	0.20	0.12	0.88	0.40	0.02	0.20	0.12	0.87	0.40
Belgium	0.51	0.91	0.90	1.66	1.15	0.50	0.88	0.88	1.63	1.13	0.54	0.89	0.88	1.64	1.14
Bulgaria	0.07	0.41	0.33	1.08	0.61	0.07	0.40	0.32	1.08	0.60	0.08	0.40	0.32	1.07	0.60
Canada	2.00	22.66	2.94	3.70	9.77	1.99	22.72	2.99	3.75	9.82	1.89	22.68	2.95	3.71	9.78
Croatia	0.10	0.91	0.22	0.97	0.70	0.09	0.91	0.21	0.97	0.69	0.10	0.90	0.21	0.97	0.69
Czechia	0.23	0.64	0.60	2.12	1.12	0.22	0.62	0.58	2.10	1.10	0.22	0.62	0.58	2.09	1.10
Denmark	0.42	1.24	0.53	2.04	1.27	0.43	1.23	0.51	2.03	1.26	0.43	1.23	0.52	2.03	1.26
Estonia	0.04	0.47	8.27	2.34	3.70	0.04	0.47	8.27	2.34	3.70	0.05	0.47	8.27	2.34	3.70
France	5.06	5.62	5.09	5.85	5.52	4.89	5.47	4.93	5.69	5.36	5.31	5.49	4.96	5.72	5.39
Germany	4.22	6.88	6.53	8.05	7.15	4.27	6.68	6.34	7.85	6.96	4.52	6.74	6.39	7.91	7.01
Greece	0.67	2.03	0.67	1.43	1.38	0.58	1.99	0.63	1.39	1.34	0.58	1.97	0.61	1.37	1.32
Hungary	0.14	0.56	0.50	2.02	1.03	0.13	0.55	0.49	2.00	1.01	0.13	0.54	0.48	2.00	1.01
Italy	3.16	5.20	4.34	5.10	4.88	2.90	5.01	4.16	4.92	4.70	3.06	5.00	4.15	4.91	4.69
Latvia	0.03	0.20	8.50	2.37	3.69	0.02	0.20	8.50	2.37	3.69	0.03	0.20	8.50	2.37	3.69
Lithuania	0.03	0.25	6.76	2.42	3.14	0.03	0.25	6.76	2.42	3.14	0.04	0.25	6.76	2.42	3.14
Luxembourg	0.02	0.08	0.08	0.83	0.33	0.02	0.08	0.08	0.83	0.33	0.02	0.08	0.08	0.84	0.33
Montenegro															
Netherlands	1.09	1.51	1.47	2.23	1.74	1.01	1.45	1.41	2.17	1.68	1.04	1.46	1.41	2.17	1.68
N. Macedonia															
Norway	0.68	3.36	5.48	2.92	3.92	0.70	3.37	5.50	2.94	3.94	0.75	3.37	5.50	2.93	3.93
Poland	0.88	2.05	7.19	4.17	4.47	0.88	2.02	7.16	4.14	4.44	0.95	2.02	7.15	4.13	4.43
Portugal	0.34	0.79	0.62	1.38	0.93	0.30	0.77	0.59	1.35	0.90	0.33	0.76	0.59	1.34	0.90
Romania	0.22	1.12	0.92	2.44	1.50	0.20	1.10	0.91	2.42	1.48	0.25	1.10	0.90	2.42	1.47
Slovakia	0.10	0.30	0.29	1.81	0.80	0.10	0.30	0.29	1.80	0.80	0.10	0.30	0.29	1.80	0.80
Slovenia	0.06	0.16	0.12	0.88	0.39	0.05	0.15	0.12	0.88	0.38	0.05	0.15	0.12	0.88	0.38
Spain	1.84	3.61	3.11	3.87	3.53	1.84	3.46	2.97	3.73	3.39	1.76	3.43	2.94	3.69	3.35
Turkey	1.59	4.44	3.52	5.04	4.33	1.72	4.51	3.59	5.11	4.40	1.88	4.56	3.65	5.16	4.46
UK	6.22	6.08	4.82	5.58	5.49	6.37	6.15	4.89	5.64	5.56	6.52	6.12	4.86	5.62	5.54
United States	70.27	28.31	26.06	26.82	27.06	70.63	29.07	26.81	27.57	27.82	69.35	29.07	26.82	27.58	27.82

Continued on next page

	2014					2015					2016				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania	0.02	0.20	0.12	0.87	0.40	0.01	0.20	0.11	0.87	0.39	0.01	0.20	0.11	0.87	0.39
Belgium	0.55	0.88	0.88	1.64	1.13	0.47	0.84	0.83	1.59	1.09	0.47	0.84	0.84	1.59	1.09
Bulgaria	0.08	0.40	0.31	1.07	0.59	0.07	0.39	0.31	1.06	0.59	0.07	0.39	0.31	1.06	0.59
Canada	1.88	22.59	2.87	3.62	9.69	2.00	22.45	2.72	3.48	9.55	1.96	22.41	2.68	3.44	9.51
Croatia	0.11	0.90	0.20	0.96	0.69	0.10	0.89	0.20	0.95	0.68	0.09	0.89	0.20	0.95	0.68
Czechia	0.21	0.61	0.57	2.08	1.09	0.20	0.59	0.56	2.07	1.07	0.22	0.60	0.56	2.07	1.08
Denmark	0.43	1.23	0.51	2.03	1.26	0.37	1.20	0.48	2.00	1.23	0.40	1.20	0.49	2.00	1.23
Estonia	0.05	0.47	8.27	2.34	3.70	0.05	0.47	8.27	2.34	3.69	0.05	0.47	8.27	2.34	3.69
France	5.60	5.44	4.91	5.67	5.34	5.08	5.18	4.65	5.41	5.08	5.23	5.17	4.64	5.40	5.07
Germany	4.70	6.76	6.41	7.93	7.03	4.25	6.45	6.10	7.62	6.72	4.40	6.51	6.17	7.68	6.79
Greece	0.58	1.96	0.60	1.36	1.31	0.54	1.93	0.57	1.33	1.28	0.55	1.92	0.56	1.32	1.27
Hungary	0.13	0.54	0.48	2.00	1.01	0.13	0.53	0.47	1.99	1.00	0.14	0.53	0.47	1.98	0.99
Italy	2.92	4.96	4.11	4.87	4.65	2.47	4.75	3.89	4.65	4.43	2.76	4.74	3.89	4.65	4.43
Latvia	0.03	0.20	8.50	2.37	3.69	0.03	0.19	8.50	2.37	3.69	0.04	0.19	8.50	2.37	3.69
Lithuania	0.04	0.25	6.75	2.42	3.14	0.05	0.24	6.75	2.42	3.14	0.07	0.24	6.75	2.41	3.13
Luxembourg	0.03	0.08	0.08	0.84	0.33	0.03	0.08	0.08	0.83	0.33	0.03	0.08	0.08	0.83	0.33
Montenegro															
Netherlands	1.09	1.45	1.40	2.16	1.67	0.96	1.37	1.33	2.08	1.59	1.01	1.38	1.33	2.09	1.60
N. Macedonia															
Norway	0.77	3.33	5.46	2.90	3.90	0.65	3.25	5.38	2.82	3.82	0.66	3.23	5.36	2.80	3.80
Poland	1.09	2.01	7.15	4.13	4.43	1.14	1.97	7.10	4.09	4.39	1.01	1.95	7.08	4.07	4.37
Portugal	0.32	0.75	0.58	1.34	0.89	0.29	0.73	0.56	1.32	0.87	0.35	0.73	0.56	1.32	0.87
Romania	0.28	1.10	0.90	2.41	1.47	0.29	1.08	0.88	2.40	1.45	0.29	1.08	0.88	2.39	1.45
Slovakia	0.11	0.30	0.29	1.80	0.79	0.11	0.29	0.28	1.79	0.79	0.11	0.29	0.28	1.79	0.79
Slovenia	0.05	0.15	0.12	0.88	0.38	0.04	0.15	0.11	0.87	0.38	0.05	0.15	0.11	0.87	0.38
Spain	1.81	3.39	2.90	3.65	3.31	1.69	3.28	2.79	3.55	3.20	1.55	3.29	2.80	3.56	3.21
Turkey	1.85	4.54	3.63	5.14	4.44	1.74	4.54	3.62	5.14	4.43	1.97	4.55	3.64	5.15	4.45
UK	7.06	6.29	5.03	5.79	5.70	6.68	6.31	5.05	5.80	5.72	5.89	6.06	4.80	5.55	5.47
United States	68.22	29.23	26.97	27.73	27.98	70.56	30.67	28.42	29.17	29.42	70.61	30.91	28.66	29.42	29.66

Continued on next page

	2017					2018					2019				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania	0.02	0.18	0.11	0.85	0.38	0.02	0.18	0.11	0.86	0.38	0.02	0.18	0.11	0.85	0.38
Belgium	0.48	0.85	0.84	1.58	1.09	0.49	0.86	0.85	1.59	1.10	0.46	0.85	0.84	1.58	1.09
Bulgaria	0.08	0.39	0.30	1.05	0.58	0.10	0.39	0.30	1.04	0.58	0.21	0.39	0.30	1.04	0.58
Canada	2.40	22.43	2.73	3.48	9.55	2.30	22.42	2.73	3.47	9.54	2.14	22.43	2.74	3.48	9.55
Croatia	0.10	0.89	0.19	0.93	0.67	0.10	0.88	0.19	0.93	0.67	0.09	0.88	0.19	0.93	0.67
Czechia	0.22	0.61	0.57	2.05	1.08	0.27	0.62	0.58	2.07	1.09	0.28	0.62	0.58	2.07	1.09
Denmark	0.41	1.21	0.49	1.97	1.22	0.46	1.21	0.50	1.98	1.23	0.43	1.20	0.48	1.97	1.22
Estonia	0.06	0.47	8.27	2.29	3.68	0.06	0.47	8.27	2.29	3.68	0.06	0.47	8.27	2.29	3.68
France	5.30	5.16	4.63	5.38	5.06	5.20	5.19	4.66	5.40	5.08	4.80	5.11	4.58	5.32	5.00
Germany	4.56	6.56	6.21	7.70	6.82	4.70	6.60	6.26	7.74	6.86	4.70	6.47	6.13	7.61	6.74
Greece	0.55	1.91	0.56	1.30	1.26	0.58	1.91	0.56	1.30	1.25	0.52	1.90	0.55	1.29	1.25
Hungary	0.18	0.53	0.47	1.96	0.99	0.16	0.54	0.48	1.96	0.99	0.21	0.54	0.48	1.96	0.99
Italy	2.85	4.72	3.87	4.61	4.40	2.87	4.72	3.86	4.60	4.39	2.53	4.59	3.74	4.48	4.27
Latvia	0.05	0.19	8.50	2.32	3.67	0.07	0.19	8.50	2.32	3.67	0.07	0.19	8.50	2.32	3.67
Lithuania	0.09	0.24	6.75	2.36	3.12	0.11	0.24	6.75	2.37	3.12	0.10	0.24	6.75	2.37	3.12
Luxembourg	0.03	0.08	0.08	0.82	0.33	0.04	0.08	0.08	0.82	0.33	0.04	0.08	0.08	0.82	0.33
Montenegro	0.01	0.10	0.03	0.77	0.30	0.01	0.10	0.03	0.77	0.30	0.01	0.10	0.03	0.77	0.30
Netherlands	1.03	1.39	1.35	2.09	1.61	1.12	1.42	1.37	2.11	1.63	1.15	1.41	1.36	2.10	1.62
N. Macedonia															
Norway	0.74	3.24	5.37	2.76	3.79	0.76	3.25	5.38	2.77	3.80	0.72	3.22	5.35	2.74	3.77
Poland	1.06	1.97	7.11	4.04	4.37	1.22	1.99	7.13	4.06	4.39	1.13	1.99	7.12	4.05	4.39
Portugal	0.29	0.73	0.56	1.30	0.86	0.33	0.74	0.56	1.30	0.87	0.32	0.73	0.56	1.30	0.86
Romania	0.39	1.08	0.88	2.36	1.44	0.44	1.09	0.89	2.37	1.45	0.44	1.09	0.89	2.37	1.45
Slovakia	0.11	0.29	0.28	1.76	0.77	0.13	0.29	0.28	1.76	0.78	0.17	0.29	0.28	1.76	0.78
Slovenia	0.05	0.15	0.12	0.86	0.37	0.05	0.15	0.12	0.86	0.38	0.05	0.15	0.12	0.86	0.38
Spain	1.73	3.30	2.81	3.55	3.22	1.80	3.33	2.83	3.57	3.24	1.65	3.29	2.80	3.54	3.21
Turkey	1.92	4.53	3.62	5.10	4.41	1.99	4.45	3.53	5.01	4.33	1.96	4.45	3.54	5.02	4.34
UK	5.61	5.94	4.68	5.42	5.35	5.64	5.97	4.71	5.45	5.37	5.42	5.92	4.66	5.40	5.33
United States	69.68	30.86	28.61	29.35	29.60	68.98	30.73	28.48	29.22	29.48	70.33	31.22	28.97	29.71	29.96

Continued on next page

	2020					2021					2022				
	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4	DB	ABS 1	ABS 2	ABS 3	ABS 4
Albania	0.02	0.16	0.11	0.84	0.37	0.02	0.16	0.11	0.84	0.37	0.02	0.16	0.11	0.84	0.37
Belgium	0.48	0.85	0.84	1.57	1.08	0.54	0.85	0.84	1.57	1.09	0.57	0.83	0.82	1.55	1.07
Bulgaria	0.10	0.37	0.30	1.03	0.57	0.11	0.37	0.30	1.03	0.57	0.12	0.36	0.30	1.02	0.56
Canada	2.09	22.41	2.70	3.42	9.51	2.18	22.52	2.81	3.54	9.62	2.11	22.58	2.87	3.59	9.68
Croatia	0.09	0.88	0.19	0.91	0.66	0.12	0.88	0.19	0.91	0.66	0.11	0.88	0.18	0.91	0.66
Czechia	0.29	0.62	0.58	2.03	1.08	0.34	0.62	0.58	2.03	1.08	0.33	0.62	0.58	2.03	1.08
Denmark	0.44	1.21	0.50	1.95	1.22	0.45	1.22	0.50	1.95	1.22	0.45	1.20	0.49	1.94	1.21
Estonia	0.06	0.47	8.27	2.25	3.66	0.06	0.48	8.27	2.25	3.67	0.07	0.48	8.27	2.25	3.67
France	4.77	5.08	4.55	5.28	4.97	4.87	5.08	4.55	5.28	4.97	4.43	4.86	4.33	5.06	4.75
Germany	4.82	6.51	6.16	7.61	6.76	4.86	6.45	6.10	7.55	6.70	4.64	6.18	5.83	7.28	6.43
Greece	0.52	1.87	0.53	1.26	1.22	0.71	1.87	0.53	1.26	1.22	0.72	1.86	0.52	1.24	1.21
Hungary	0.25	0.53	0.47	1.92	0.98	0.21	0.53	0.47	1.92	0.98	0.27	0.52	0.46	1.91	0.96
Italy	2.98	4.51	3.66	4.38	4.18	3.11	4.52	3.67	4.40	4.20	2.87	4.38	3.53	4.26	4.06
Latvia	0.07	0.19	8.50	2.27	3.65	0.07	0.19	8.50	2.27	3.65	0.07	0.19	8.50	2.27	3.65
Lithuania	0.11	0.24	6.75	2.32	3.10	0.11	0.24	6.75	2.32	3.11	0.14	0.25	6.75	2.32	3.11
Luxembourg	0.04	0.08	0.08	0.81	0.32	0.03	0.09	0.08	0.81	0.33	0.04	0.08	0.08	0.80	0.32
Montenegro	0.01	0.10	0.03	0.75	0.29	0.01	0.10	0.03	0.75	0.29	0.01	0.10	0.03	0.75	0.29
Netherlands	1.18	1.42	1.38	2.10	1.64	1.24	1.43	1.39	2.11	1.64	1.13	1.39	1.35	2.07	1.60
N. Macedonia	0.01	0.10	0.08	0.80	0.33	0.02	0.10	0.07	0.80	0.32	0.02	0.10	0.07	0.80	0.32
Norway	0.65	3.19	5.33	2.67	3.73	0.72	3.26	5.39	2.73	3.79	0.72	3.31	5.44	2.78	3.84
Poland	1.24	1.99	7.12	4.01	4.37	1.31	1.96	7.09	3.98	4.34	1.27	1.93	7.06	3.95	4.31
Portugal	0.30	0.73	0.55	1.28	0.85	0.33	0.73	0.55	1.28	0.85	0.29	0.72	0.54	1.27	0.84
Romania	0.46	1.08	0.89	2.33	1.43	0.46	1.08	0.88	2.33	1.43	0.43	1.07	0.87	2.32	1.42
Slovakia	0.19	0.29	0.28	1.73	0.77	0.18	0.29	0.28	1.73	0.77	0.17	0.28	0.27	1.72	0.76
Slovenia	0.05	0.15	0.12	0.84	0.37	0.07	0.15	0.12	0.84	0.37	0.06	0.15	0.12	0.84	0.37
Spain	1.58	3.22	2.73	3.45	3.13	1.68	3.23	2.74	3.46	3.14	1.68	3.17	2.68	3.40	3.09
Turkey	1.58	4.44	3.53	4.98	4.32	1.34	4.47	3.56	5.01	4.35	0.89	4.52	3.61	5.06	4.40
UK	5.27	5.84	4.58	5.30	5.24	5.60	5.91	4.65	5.38	5.31	5.29	5.80	4.54	5.27	5.20
United States	70.36	31.45	29.20	29.93	30.19	69.27	31.21	28.96	29.69	29.95	71.09	32.03	29.78	30.50	30.77

(*Notes.* The table presents defense burdens (measured as military expenditure over GDP) and alternative specifications of the Average Benefit Share (ABS) for NATO from 1993 to 2022. Each ABS combines GDP, population, and one threat-related component, weighted equally. ABS 1 is based on total exposed land borders; ABS 2 uses only borders exposed to Russia; and ABS 3 using a distance category; ABS 4. uses weighted composite of GDP, population size, and including three threat dimensions: exposed land borders, exposed borders with Russia, and a distance category. Defense burden and ABS values are normalized to sum to 100% across countries in each year.)

B.7 | Robustness Checks: Alternative Weighting of Benefit Shares

To test the sensitivity of our results to the specific weighting scheme applied in the baseline ABS, we conduct a robustness analysis using three alternative weighting specifications. Our baseline measure equally weights three dimensions: GDP (economic capacity), population (security beneficiaries), and a proxy for threat. While this equal-weighting scheme is theoretically balanced, it is ultimately a modeling choice. To ensure our conclusions are not sensitive to this assumption, we introduce three alternative average benefit shares:

- GDP-focused: 50% GDP, 25% population, 25% threat
- Population-focused: 25% GDP, 50% population, 25% threat
- Threat-focused: 25% GDP, 25% population, 50% threat

We recalculate the four ABSs (ABS 1–4) using these alternative weights and apply Wilcoxon signed-rank tests for all European NATO members and NATO members over the period 1993-2022. The results are summarized in Tables B.11, B.12, and B.13.

The results, presented in Tables for European NATO B.11, B.12 and B.13 indicate that our main conclusions hold under these alternative assumptions. We observe statistically significant deviations from benefit-burden concordance in the same periods previously identified. This suggests that our findings are not driven by an arbitrary choice of weights, but rather reflect persistent structural imbalances in European NATO burden-sharing.

B.7.1 | European NATO

When examining all four tables—Table 3.3, Table B.11, Table B.12, and Table B.13—it is evident that ABS 2 consistently stands out. Across all weighting schemes, the null hypothesis cannot be rejected for this average benefit share. This indicates that there is no statistically significant loss of concordance, making it a statistically robust average benefit share for explaining defense burdens. An exception arises under the threat-focused weighting scheme, where the null hypothesis is rejected during the years 1993–2003. This period coincides with NATO enlargement, during which several new members geographically closer to Russia joined the alliance. Moreover, the threat-focused specification produces noticeably different outcomes for the other average benefit shares as well, whereas the results across the other weighting schemes remain largely stable across most years, apart from minor fluctuations. The specific details are discussed in the following paragraph.

Table B.11 presents the results of the Wilcoxon tests of the GDP-focused alternative average benefit share. For ABS 1, we reject the null hypothesis at the 0.05 significance level for the period 2004–2019, and additionally in 2018 and 2019 at the 0.1 level. For ABS 2, the null hypothesis cannot be rejected. In contrast, for ABS 3 and ABS 4, the null hypothesis is rejected at the 0.1 significance level or better across the full period from 2004 to 2021. These results indicate that increasing GDP weights amplifies burden-sharing asymmetries among European NATO members—particularly after the alliance's eastward enlargement in 2004, when several lower-income countries joined. Notably, ABS 2 proves robust to the GDP weighting.

Table B.12 presents the results of the Wilcoxon tests using the population-weighted alternative average benefit share. For ABS 1, we reject the null hypothesis at the 0.1 significance level in the years 2005–2007, 2010, and 2012–2019. In the case of ABS 2, the null hypothesis cannot be rejected. For ABS 3, we reject the null hypothesis for the period 2004–2020, with the exception of 2009. Regarding ABS 4, the null hypothesis is rejected in the years 2005–2007 and 2010–2021 at the 0.1 level or better. These findings indicate that increasing the weight on the population also amplifies burden-sharing asymmetries and extends the periods in which the null hypothesis is rejected, compared to the equally weighted average benefit shares. However, the amplification effect is less pronounced than under the GDP-focused alternatives. As in the GDP-focused case, ABS 2 appears robust to changes in weighting.

Table B.13 presents the results of the Wilcoxon tests based on the threat-focused average benefit share. The null hypothesis cannot be rejected for ABS 1 and ABS 4. For ABS 2, it is only rejected prior to 2004. However, as discussed in Section 3.5.1, we do not place much emphasis on this early period, since Norway was the only NATO member directly bordering Russia at the time. In the case of ABS 3, the null hypothesis is rejected at the 0.1 significance level for the years 2014–2021. These findings indicate that assigning greater weight to the threat factor reduces burden-sharing asymmetries in Europe, as periods of significant deviation observed under the equally weighted specification are shortened or disappear. ABS 2 once again proves robust to changes in weighting after 2004.

Overall, these robustness checks indicate that our findings do not hinge on the equal-weighting assumption. While some measures are more sensitive to reweighting, ABS 2 retains its statistical validity and policy relevance across all specifications. This supports its use as a consistent indicator of the distribution of defense-related benefits in Europe.

Table B.11: Wilcoxon signed-rank correlation of ME/European NATO ME and the GDP-focused Average Benefit Shares

		Average Benefit Share 1	Average Benefit Share 2	Average Benefit Share 3	Average Benefit Share 4
Year	Size	R (p)	R (p)	R (p)	R (p)
1993	13	35 (0.5)	27 (0.22)	25 (0.17)	29 (0.27)
1994	13	33 (0.41)	29 (0.27)	25 (0.17)	26 (0.19)
1995	13	38 (0.64)	28 (0.24)	25 (0.17)	33 (0.41)
1996	13	35 (0.5)	22 (0.11)	25 (0.17)	30 (0.31)
1997	13	31 (0.34)	24 (0.15)	25 (0.17)	26 (0.19)
1998	13	31 (0.34)	22 (0.11)	28 (0.24)	29 (0.27)
1999	16	46 (0.27)	45 (0.25)	42 (0.19)	52 (0.43)
2000	16	43 (0.21)	44 (0.23)	43 (0.21)	47 (0.3)
2001	16	43 (0.21)	49 (0.35)	43 (0.21)	46 (0.27)
2002	16	41 (0.18)	50 (0.38)	42 (0.19)	43 (0.21)
2003	16	44 (0.23)	53 (0.46)	41 (0.18)	43 (0.21)
2004	23	72** (0.04)	124 (0.69)	69** (0.04)	69** (0.04)
2005	23	73** (0.05)	120 (0.6)	75* (0.06)	72** (0.04)
2006	23	68** (0.03)	126 (0.73)	72** (0.04)	73** (0.05)
2007	23	58** (0.01)	120 (0.6)	69** (0.04)	70** (0.04)
2008	23	73** (0.05)	136 (0.96)	76* (0.06)	79* (0.07)
2009	25	79** (0.02)	155 (0.85)	84** (0.03)	99* (0.09)
2010	25	79** (0.02)	154 (0.83)	81** (0.03)	87** (0.04)
2011	25	90* (0.05)	150 (0.75)	76** (0.02)	85** (0.04)
2012	25	79** (0.02)	151 (0.77)	73** (0.01)	87** (0.04)
2013	25	80** (0.03)	150 (0.75)	71** (0.01)	84** (0.03)
2014	25	77** (0.02)	147 (0.69)	63*** (0.01)	76** (0.02)
2015	25	85** (0.04)	149 (0.73)	59*** (0)	67*** (0.01)
2016	25	87** (0.04)	146 (0.67)	72** (0.01)	87** (0.04)
2017	26	93** (0.04)	162 (0.75)	82** (0.02)	91** (0.03)
2018	26	102* (0.06)	170 (0.9)	84** (0.02)	100* (0.06)
2019	26	107* (0.08)	165 (0.8)	83** (0.02)	101* (0.06)
2020	27	128 (0.15)	183 (0.9)	102** (0.04)	110* (0.06)
2021	27	130 (0.16)	183 (0.9)	114* (0.07)	118* (0.09)
2022	27	145 (0.3)	169 (0.64)	120 (0.1)	124 (0.12)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. The construction of Average Benefit Shares are explained in the first paragraph of 3.5.1 and the alternative weightings in B.7. In parentheses are prob-values, indicating the probability of a type I error.

***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

Table B.12: Wilcoxon signed-rank correlation of ME/European NATO ME and the population-focused Average Benefit Shares

		Average Benefit Share 1	Average Benefit Share 2	Average Benefit Share 3	Average Benefit Share 4
Year	Size	R (p)	R (p)	R (p)	R (p)
1993	13	39 (0.68)	36 (0.54)	30 (0.31)	35 (0.5)
1994	13	39 (0.68)	35 (0.5)	27 (0.22)	35 (0.5)
1995	13	40 (0.74)	33 (0.41)	31 (0.34)	35 (0.5)
1996	13	39 (0.68)	30 (0.31)	29 (0.27)	36 (0.54)
1997	13	37 (0.59)	32 (0.38)	26 (0.19)	36 (0.54)
1998	13	37 (0.59)	31 (0.34)	29 (0.27)	37 (0.59)
1999	16	53 (0.46)	57 (0.6)	48 (0.32)	56 (0.56)
2000	16	54 (0.5)	57 (0.6)	45 (0.25)	55 (0.53)
2001	16	56 (0.56)	57 (0.6)	47 (0.3)	55 (0.53)
2002	16	51 (0.4)	61 (0.74)	44 (0.23)	52 (0.43)
2003	16	53 (0.46)	61 (0.74)	43 (0.21)	52 (0.43)
2004	23	90 (0.15)	118 (0.56)	74* (0.05)	86 (0.12)
2005	23	77* (0.07)	111 (0.43)	76* (0.06)	77* (0.07)
2006	23	83* (0.1)	120 (0.6)	78* (0.07)	83* (0.1)
2007	23	79* (0.07)	119 (0.58)	76* (0.06)	83* (0.1)
2008	23	90 (0.15)	125 (0.71)	82* (0.09)	93 (0.18)
2009	25	101 (0.1)	141 (0.58)	101 (0.1)	106 (0.13)
2010	25	100* (0.1)	141 (0.58)	95* (0.07)	98* (0.09)
2011	25	103 (0.11)	137 (0.51)	90* (0.05)	95* (0.07)
2012	25	91* (0.06)	139 (0.54)	89** (0.05)	95* (0.07)
2013	25	92* (0.06)	134 (0.46)	87** (0.04)	93* (0.06)
2014	25	86** (0.04)	129 (0.38)	85** (0.04)	90* (0.05)
2015	25	82** (0.03)	126 (0.34)	74** (0.02)	78** (0.02)
2016	25	87** (0.04)	126 (0.34)	87** (0.04)	95* (0.07)
2017	26	94** (0.04)	141 (0.39)	94** (0.04)	104* (0.07)
2018	26	94** (0.04)	143 (0.42)	96** (0.04)	106* (0.08)
2019	26	93** (0.04)	144 (0.44)	96** (0.04)	99* (0.05)
2020	27	120 (0.1)	147 (0.32)	115* (0.08)	114* (0.07)
2021	27	128 (0.15)	152 (0.39)	125 (0.13)	116* (0.08)
2022	27	139 (0.24)	170 (0.66)	126 (0.13)	123 (0.12)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. The construction of Average Benefit Shares are explained in the first paragraph of 3.5.1and the alternative weightings in B.7. In parentheses are prob-values, indicating the probability of a type I error.
***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

Table B.13: Wilcoxon signed-rank correlation of ME/European NATO ME and the threat-focused Average Benefit Shares

		Average Benefit Share 1	Average Benefit Share 2	Average Benefit Share 3	Average Benefit Share 4
Year	Size	R (p)	R (p)	R (p)	R (p)
1993	13	43 (0.89)	14** (0.03)	36 (0.54)	44 (0.95)
1994	13	43 (0.89)	18* (0.06)	36 (0.54)	45 (1)
1995	13	43 (0.89)	17** (0.05)	34 (0.45)	45 (1)
1996	13	44 (0.95)	16** (0.04)	37 (0.59)	43 (0.89)
1997	13	45 (1)	14** (0.03)	35 (0.5)	45 (1)
1998	13	45 (1)	14** (0.03)	35 (0.5)	45 (1)
1999	16	64 (0.86)	38 (0.13)	53 (0.46)	62 (0.78)
2000	16	64 (0.86)	37 (0.12)	53 (0.46)	64 (0.86)
2001	16	66 (0.94)	34* (0.08)	52 (0.43)	62 (0.78)
2002	16	62 (0.78)	34* (0.08)	50 (0.38)	59 (0.67)
2003	16	62 (0.78)	34* (0.08)	51 (0.4)	59 (0.67)
2004	23	107 (0.36)	116 (0.52)	90 (0.15)	100 (0.26)
2005	23	110 (0.41)	113 (0.46)	84 (0.1)	103 (0.3)
2006	23	105 (0.33)	116 (0.52)	93 (0.18)	103 (0.3)
2007	23	110 (0.41)	113 (0.46)	94 (0.19)	105 (0.33)
2008	23	113 (0.46)	111 (0.43)	97 (0.22)	108 (0.38)
2009	25	122 (0.29)	135 (0.47)	117 (0.23)	120 (0.26)
2010	25	124 (0.31)	137 (0.51)	112 (0.18)	118 (0.24)
2011	25	125 (0.33)	138 (0.52)	108 (0.15)	119 (0.25)
2012	25	128 (0.37)	141 (0.58)	108 (0.15)	116 (0.22)
2013	25	120 (0.26)	143 (0.62)	103 (0.11)	112 (0.18)
2014	25	119 (0.25)	143 (0.62)	99* (0.09)	110 (0.16)
2015	25	116 (0.22)	140 (0.56)	95* (0.07)	110 (0.16)
2016	25	122 (0.29)	137 (0.51)	100* (0.1)	113 (0.19)
2017	26	135 (0.32)	127 (0.23)	108* (0.09)	126 (0.22)
2018	26	143 (0.42)	130 (0.26)	110* (0.1)	129 (0.25)
2019	26	138 (0.35)	115 (0.13)	110* (0.1)	128 (0.24)
2020	27	154 (0.41)	132 (0.18)	112* (0.07)	130 (0.16)
2021	27	156 (0.44)	133 (0.19)	115* (0.08)	131 (0.17)
2022	27	168 (0.63)	140 (0.25)	122 (0.11)	139 (0.24)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. The construction of Average Benefit Shares are explained in the first paragraph of 3.5.1and the alternative weightings in B.7. In parentheses are prob-values, indicating the probability of a type I error.
***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

B.7.2 | NATO

For NATO as a whole, the results of the Wilcoxon tests using GDP-, population-, and threat-focused average benefit shares are presented in Tables B.14, B.15, and B.16, respectively. The observed patterns mirror those found for the European NATO members. Assigning greater weight to GDP and population tends to amplify burden-sharing asymmetries, while the threat-focused weighting mitigates them. However, these weighting effects are largely limited to the period prior to 2004. An exception is ABS 2 in the threat-focused case, where the null hypothesis is rejected in 2005, 2006, and 2009–2019 at the 0.1 significance level or better. In contrast, under the equally weighted specification, the null hypothesis for ABS 2 is consistently rejected throughout the entire period from 2004 to 2022 at the 0.01 level.

Table B.14: Wilcoxon signed-rank correlation of ME/NATO ME and GDP-focused Average Benefit Shares

		Average Benefit Share 1	Average Benefit Share 2	Average Benefit Share 3	Average Benefit Share 4
Year	Size	R (p)	R (p)	R (p)	R (p)
1993	15	24** (0.04)	34 (0.15)	17** (0.01)	24** (0.04)
1994	15	29* (0.08)	36 (0.19)	17** (0.01)	25** (0.05)
1995	15	29* (0.08)	40 (0.28)	18** (0.02)	29* (0.08)
1996	15	30* (0.09)	42 (0.33)	18** (0.02)	29* (0.08)
1997	15	29* (0.08)	41 (0.3)	18** (0.02)	28* (0.07)
1998	15	30* (0.09)	43 (0.36)	18** (0.02)	27* (0.06)
1999	18	38** (0.04)	54 (0.18)	26*** (0.01)	36** (0.03)
2000	18	28** (0.01)	45* (0.08)	22*** (0)	30** (0.01)
2001	18	28** (0.01)	40** (0.05)	22*** (0)	29** (0.01)
2002	18	27*** (0.01)	36** (0.03)	20*** (0)	28** (0.01)
2003	18	27*** (0.01)	36** (0.03)	19*** (0)	28** (0.01)
2004	25	41*** (0)	53*** (0)	34*** (0)	39*** (0)
2005	25	39*** (0)	47*** (0)	32*** (0)	39*** (0)
2006	25	39*** (0)	48*** (0)	32*** (0)	39*** (0)
2007	25	41*** (0)	48*** (0)	34*** (0)	39*** (0)
2008	25	37*** (0)	49*** (0)	30*** (0)	38*** (0)
2009	27	27*** (0)	51*** (0)	28*** (0)	32*** (0)
2010	27	27*** (0)	43*** (0)	28*** (0)	28*** (0)
2011	27	27*** (0)	42*** (0)	28*** (0)	28*** (0)
2012	27	27*** (0)	43*** (0)	28*** (0)	31*** (0)
2013	27	28*** (0)	43*** (0)	28*** (0)	33*** (0)
2014	27	36*** (0)	46*** (0)	34*** (0)	42*** (0)
2015	27	27*** (0)	43*** (0)	28*** (0)	31*** (0)
2016	27	27*** (0)	43*** (0)	27*** (0)	27*** (0)
2017	28	28*** (0)	49*** (0)	28*** (0)	28*** (0)
2018	28	28*** (0)	46*** (0)	28*** (0)	28*** (0)
2019	28	28*** (0)	38*** (0)	28*** (0)	28*** (0)
2020	29	29*** (0)	41*** (0)	29*** (0)	29*** (0)
2021	29	29*** (0)	57*** (0)	29*** (0)	29*** (0)
2022	29	29*** (0)	54*** (0)	29*** (0)	29*** (0)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. The construction of Average Benefit Shares are explained in the first paragraph of 3.5.1 and the alternative weightings in B.7. In parentheses are prob-values, indicating the probability of a type I error.

***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

Table B.15: Wilcoxon signed-rank correlation of ME/NATO ME and population-focused Average Benefit Shares

		Average Benefit Share 1	Average Benefit Share 2	Average Benefit Share 3	Average Benefit Share 4
Year	Size	R (p)	R (p)	R (p)	R (p)
1993	15	26* (0.06)	32 (0.12)	17** (0.01)	22** (0.03)
1994	15	28* (0.07)	33 (0.14)	18** (0.02)	26* (0.06)
1995	15	29* (0.08)	37 (0.21)	18** (0.02)	30* (0.09)
1996	15	29* (0.08)	41 (0.3)	18** (0.02)	30* (0.09)
1997	15	29* (0.08)	37 (0.21)	17** (0.01)	26* (0.06)
1998	15	28* (0.07)	38 (0.23)	19** (0.02)	25** (0.05)
1999	18	37** (0.03)	48 (0.11)	26*** (0.01)	35** (0.03)
2000	18	28** (0.01)	38** (0.04)	24*** (0.01)	29** (0.01)
2001	18	28** (0.01)	38** (0.04)	23*** (0)	28** (0.01)
2002	18	27*** (0.01)	31** (0.02)	22*** (0)	28** (0.01)
2003	18	27*** (0.01)	33** (0.02)	22*** (0)	28** (0.01)
2004	25	42*** (0)	49*** (0)	40*** (0)	42*** (0)
2005	25	41*** (0)	47*** (0)	36*** (0)	39*** (0)
2006	25	41*** (0)	45*** (0)	35*** (0)	39*** (0)
2007	25	42*** (0)	48*** (0)	40*** (0)	40*** (0)
2008	25	40*** (0)	47*** (0)	34*** (0)	38*** (0)
2009	27	28*** (0)	48*** (0)	28*** (0)	32*** (0)
2010	27	27*** (0)	42*** (0)	28*** (0)	30*** (0)
2011	27	27*** (0)	42*** (0)	28*** (0)	30*** (0)
2012	27	28*** (0)	42*** (0)	28*** (0)	31*** (0)
2013	27	30*** (0)	43*** (0)	28*** (0)	34*** (0)
2014	27	42*** (0)	47*** (0)	35*** (0)	42*** (0)
2015	27	31*** (0)	44*** (0)	28*** (0)	34*** (0)
2016	27	27*** (0)	42*** (0)	27*** (0)	28*** (0)
2017	28	28*** (0)	41*** (0)	28*** (0)	28*** (0)
2018	28	28*** (0)	39*** (0)	28*** (0)	28*** (0)
2019	28	28*** (0)	35*** (0)	28*** (0)	28*** (0)
2020	29	29*** (0)	32*** (0)	29*** (0)	29*** (0)
2021	29	29*** (0)	43*** (0)	29*** (0)	29*** (0)
2022	29	29*** (0)	39*** (0)	29*** (0)	29*** (0)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. The construction of Average Benefit Shares are explained in the first paragraph of 3.5.1 and the alternative weightings in B.7. In parentheses are prob-values, indicating the probability of a type I error.
***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

Table B.16: Wilcoxon signed-rank correlation of ME/NATO ME and threat-focused Average Benefit Shares

		Average Benefit Share 1	Average Benefit Share 2	Average Benefit Share 3	Average Benefit Share 4
Year	Size	R (p)	R (p)	R (p)	R (p)
1993	15	39 (0.25)	49 (0.56)	18** (0.02)	35 (0.17)
1994	15	42 (0.33)	45 (0.42)	18** (0.02)	36 (0.19)
1995	15	46 (0.45)	38 (0.23)	18** (0.02)	36 (0.19)
1996	15	48 (0.52)	33 (0.14)	18** (0.02)	36 (0.19)
1997	15	45 (0.42)	40 (0.28)	18** (0.02)	36 (0.19)
1998	15	47 (0.49)	37 (0.21)	20** (0.02)	37 (0.21)
1999	18	57 (0.23)	63 (0.35)	30** (0.01)	45* (0.08)
2000	18	49 (0.12)	73 (0.61)	29** (0.01)	41* (0.05)
2001	18	47* (0.1)	82 (0.9)	29** (0.01)	40** (0.05)
2002	18	43* (0.07)	78 (0.77)	26*** (0.01)	38** (0.04)
2003	18	46* (0.09)	77 (0.73)	27*** (0.01)	38** (0.04)
2004	25	68*** (0.01)	103 (0.11)	46*** (0)	59*** (0)
2005	25	66*** (0.01)	100* (0.1)	42*** (0)	57*** (0)
2006	25	63*** (0.01)	100* (0.1)	41*** (0)	57*** (0)
2007	25	68*** (0.01)	103 (0.11)	44*** (0)	57*** (0)
2008	25	62*** (0.01)	102 (0.11)	39*** (0)	55*** (0)
2009	27	58*** (0)	92** (0.02)	41*** (0)	59*** (0)
2010	27	55*** (0)	86** (0.01)	40*** (0)	51*** (0)
2011	27	55*** (0)	80*** (0.01)	41*** (0)	53*** (0)
2012	27	56*** (0)	78*** (0.01)	42*** (0)	52*** (0)
2013	27	62*** (0)	81*** (0.01)	42*** (0)	58*** (0)
2014	27	68*** (0)	86** (0.01)	42*** (0)	65*** (0)
2015	27	61*** (0)	78*** (0.01)	42*** (0)	57*** (0)
2016	27	58*** (0)	81*** (0.01)	32*** (0)	61*** (0)
2017	28	57*** (0)	108** (0.03)	33*** (0)	66*** (0)
2018	28	60*** (0)	125* (0.08)	33*** (0)	67*** (0)
2019	28	52*** (0)	124* (0.07)	31*** (0)	52*** (0)
2020	29	53*** (0)	154 (0.18)	32*** (0)	56*** (0)
2021	29	69*** (0)	159 (0.21)	35*** (0)	65*** (0)
2022	29	52*** (0)	153 (0.17)	33*** (0)	56*** (0)

(*Notes.* This table reports Wilcoxon signed-rank test statistics (R) and associated p-values. Each test evaluates whether countries' defense burden shares match their respective Average Benefit Share (ABS). The hypotheses are specified in 3.5.1. The construction of Average Benefit Shares are explained in the first paragraph of 3.5.1 and the alternative weightings in B.7. In parentheses are prob-values, indicating the probability of a type I error.

***significant at .01 level; **significant at .05 level; and *significant at .10 level. The critical values for rejecting the null hypothesis of match between the average benefit share and single benefit share are 17 at .05 level and 9 at .01 level for 1993–1998; are 29 at .05 level and 19 at .01 level for 1999–2003; are 73 at .05 level and 54 at .01 level for 2004–2008; are 89 at .05 level and 68 at .01 level for 2009–2016; are 98 at .05 level and 75 at .01 level for 2017–2019; are 107 at .05 level and 83 at .01 level for 2020–2022. Iceland is excluded for all years.)

CHAPTER | 4

This part is based on the joint work:

> ***Designing Rebate Rules in Public Goods Provision: Axioms, Limits, and Comparisons***,
> by Cyril Rouault and Resul Zoroğlu.

ABSTRACT

This paper examines rebate rules in the context of crowdfunding. These rules aim to redistribute the surplus when total contributions exceed the cost of the project. Using an axiomatic approach, we establish impossibility results that highlight the inherent tensions between fairness, participation incentives, and contribution incentives. To address these limitations, we propose the Proportional Rebate with Threshold Rule, which strikes a balance between these competing objectives.

CHAPTER 4

Designing Rebate Rules in Public Goods Provision

4.1 Introduction

Crowdfunding has become a key financing mechanism in diverse contexts, including innovation (Miglo, 2022), investment (Strausz, 2017), and public goods provision (Spencer et al., 2009). Through this mechanism, contributors—whether individuals, firms, or municipalities—pool resources to support a wide range of initiatives. A defining feature of crowdfunding is that if contributions fall short of the required amount, they are typically reimbursed, as on platforms like Kickstarter.[1] However, when contributions exceed the cost of the project, the surplus is generally retained. This can discourage participation, as individuals may fear overcontributing. This paper introduces an axiomatic approach to rebate rules that balance the incentives to contribute and mitigate these concerns.

The crowdfunding mechanism operates in two stages. In the first stage, potential contributors typically receive information about the project and its associated cost. Based on this information, they decide whether to participate. The project is funded if the total contributions meet or exceed the required threshold by the end of the campaign. Otherwise, contributions are either refunded, as in the *all-or-nothing* mechanism, or retained, as in the *keep-it-all* mechanism.[2] In the second stage, any surplus funds that exceed the project's cost may be redistributed among contributors. The presence of such surplus, which remains unallocated to project funding, has significant implications for individual contribution decisions (Spencer et al., 2009). The existing literature has primarily focused on the first stage, leaving the second stage relatively unexplored. We focus solely on the redistribution of surplus contributions, excluding any distribution related to the project's completion.

One commonly observed behavioral pattern is that individuals tend to reduce their contributions when they anticipate that the project will be funded regardless of their participation. This phenomenon is particularly pronounced in the case of public goods (Cason and Zubrickas, 2019), where free-riding incentives arise. To mitigate this issue, rebate rules are introduced as a mechanism to sustain participation incentives.

A fundamental objective of crowdfunding is to maximize the total amount raised. Achieving this goal depends on two critical factors: the number of contributors and the size of their individual contributions. Both dimensions play a crucial role in ensuring the financial

---

[1] In the public goods literature, this process is often referred to as reimbursement (see Marks and Croson, 1998; Zubrickas, 2014).

[2] The all-or-nothing mechanism is used by platforms such as Kickstarter, whereas Indiegogo employs the keep-it-all mechanism. See Coats et al. (2009), Chemla and Tinn (2020) and Cumming et al. (2020) for further details.

viability of a project. A larger contributor base increases the likelihood of reaching the funding goal, while higher individual contributions increase the total funds raised. Thus, the design of rebate rules must align the objective of fostering broad participation and encouraging higher contribution levels.

We adopt a model where individuals contribute a predetermined amount—and the total contributions determine the cost level of a single project. The project consists of multiple potential alternatives, with the final alternative implemented depending on the total funds raised. Specifically, the highest feasible alternative is selected, ensuring that all lower-cost alternatives are naturally incorporated as part of the project's progression. This approach reflects real-world scenarios where a project's scale or quality expands based on available funding—such as enhancing a public facility with additional features or advancing successive phases of a development initiative. Once the total amount raised is determined and the project's cost level is set, we analyze how any surplus funds are redistributed. We define three groups of axioms to structure this analysis. The first group of axioms establishes a fundamental fairness principle for the redistribution of surplus. The other two capture the main objectives of crowdfunding: incentivizing contributions and maximizing participation.

These groups are formalized as follows. Fairness is imposed by ensuring that contributors who *contribute equally receive equal redistribution.* To incentivize contributions, we introduce a *monotonicity* axiom, which establishes an economic relationship whereby an increase in an individual's contribution leads to a corresponding increase in their expected redistribution. This condition serves to mitigate strategic behaviors aimed at avoiding overcontribution. Finally, to encourage widespread participation, we impose that adding contributors should not drastically alter the redistribution received by individuals. *Consistency* axioms capture this principle.

While combining these three axiomatic principles is desirable in rebate rule design, our results indicate that satisfying all three simultaneously is impossible. Specifically, we demonstrate that no rebate rule can simultaneously ensure equal treatment and incentivize higher individual contributions (Theorem 1). Moreover, the only rebate rule that guarantees equal treatment while maximizing the number of contributors does not redistribute any surplus at all (Theorem 2).[3]

We introduce weaker versions of these axioms to address these limitations to identify a rebate rule that better balances these objectives. Specifically, we propose the *Proportional Rebate with Threshold* (PRT) rule. This rule redistributes the surplus only to contributors whose individual contributions exceed the average project cost; otherwise, they receive no rebate. In addition, the PRT rule compensates individuals who have overcontributed by reducing their effective contributions toward the average project cost. As a result, this rule is particularly relevant in settings where participants are expected to share an identical cost burden, such as public goods provision.

We introduce the Marginal Rebate Contribution to capture the increase in rebate when an individual's contribution increases. We demonstrate that the PRT rule sustains a higher

---

[3] Note that this corresponds to the rebate rule used by platforms like Kickstarter and Indiegogo.

level of redistribution in cases of overcontribution compared to rebate rules typically used, such as the *Shapley* rule and the *Proportional Rebate (PR)* rule. More precisely, under these latter rules, when individuals increase their contributions, a significant portion of their additional payment is redistributed to other contributors. We argue that the PRT rule mitigates this effect, making it a more effective rule for balancing incentives and fairness.

4.2 | Related Literature

Existing literature primarily examines how crowdfunding mechanisms are designed to encourage individual contributions. These mechanisms also attempt to reduce free-riding, a behavior in which individuals withhold contributions in anticipation that others will fund the project. Two crowdfunding mechanisms have been widely studied: all-or-nothing and keep-it-all. In the all-or-nothing mechanism, pledges are collected only if the funding goal is met, ensuring that projects receive sufficient resources before proceeding. In contrast, the keep-it-all mechanism allows project creators to retain all contributions, even if the funding goal is not reached. Coats et al. (2009), Chemla and Tinn (2020), and Cumming et al. (2020) show that the all-or-nothing mechanism generally lead to higher pledge amounts and greater project realization rates. Miglo (2022) and Béal et al. (2025) highlight the role of early backer incentives in improving funding outcomes, with Béal et al. (2025) employing an axiomatic approach to characterize reward mechanisms that encourage early contributions. However, these contributions focus on pre-funding incentives and largely overlook the management of surplus funds once the provision point is reached. Our paper contributes to this literature by providing an axiomatic analysis of post-funding surplus redistribution and its impact on participation incentives.

Rebate rules provide an alternative approach to improving contribution incentives in the second stage of crowdfunding. Marks and Croson (1998) and Spencer et al. (2009) distinguish between *refunds*, which return contributions when the funding goal is not met, and rebates, which allocate surplus funds once the threshold is exceeded. Bagnoli and Lipman (1989) demonstrates that refund guarantees within voluntary contribution mechanisms fully implement the core, ensuring efficient public goods provision. Experimental evidence from Isaac et al. (1989) and Rondeau et al. (1999) confirms that refund guarantees increase contributions. Spencer et al. (2009) compares various rebate rules and finds that *proportional rebates* are the most effective in achieving funding targets. More recently, Oezcelik et al. (2025) introduces the *Bid-Cap* rule, which limits the highest individual contributions to prevent excessive payments once the funding goal is met.

Building on this literature, we define participation incentives through an axiom that ensures an individual's increased contribution leads to a higher redistribution. We then introduce the PRT rule, which aligns with this axiom. By comparing this rule to commonly used rules, such as the *PR* rule and the *Shapley* rule, we show that the redistribution under our proposed rule is higher than in the two alternative rules. To the best of our knowledge, this paper is the first to use the Marginal Rebate Contribution to compare rebate rules.

The structure of the paper is as follows: Section 4.3 introduces the model and presents axioms used in our analysis. Section 4.4 establishes fundamental limitations in the design of rebate rules. In Section 4.5, we introduce the PRT rule and examine the axioms it satisfies. Section 4.6 provides a comparative analysis of rebate rules. Section 4.7 concludes with key insights and directions for future research.

4.3 | Model

This section introduces our model and the axioms we consider.

4.3.1 | Redistribution Problem

Let $I = \{i_1, ..., i_n\}$ be a set of *individuals*, and $P = \{P_0, P_1, ..., P_m\}$ be an ordered set of *project alternatives*, where P_0 represents the null alternative (no project is funded). Each alternative P_k represents a progressively expanded version of the project, with associated costs $c_k \in \mathbb{R}_+$ such that for any $k, k' \in \{0, ..., m\}$, with $k < k'$, we have $c_k < c_{k'}$. The cost of the null alternative P_0 is normalized to $c_0 = 0$. We assume that $m \geq 1$, meaning that at least one non-null project alternative exists. In our approach, we consider the average cost of a funded project alternative P_k, denoted by $\bar{c}_k \equiv \frac{c_k}{|I|}$.

Each agent $i \in I$ *contributes* a non-negative amount $x_i \in \mathbb{R}_+$. Let $\mathbf{x} \equiv (x_i)_{i \in I}$ be the *contribution vector*. The *total amount collected* is given by $X \equiv \sum_{i \in I} x_i$. A project alternative P_k is *funded* if and only if $c_k \leq X < c_{k+1}$.[4] The *surplus* $S \equiv X - c_k$, represents the portion of X not used to finance the project. A (*redistribution*) problem is defined by the tuple $(I, P, \mathbf{x})$. Let Π be the set of all problems.

Given a problem $(I, P, \mathbf{x}) \in \Pi$, a *redistribution* is a vector of positive real numbers $\mathbf{r} \equiv (r_i)_{i \in I} \in \mathbb{R}_+^{|I|}$ such that $\sum_{i \in I} r_i \leq S$. Let $R(I, P, \mathbf{x})$ denote the set of all redistributions for the problem $(I, P, \mathbf{x})$. A (*rebate*) *rule* is a mapping $\varphi : \Pi \to \mathbb{R}_+^{|I|}$ that assigns, to each problem $(I, P, \mathbf{x}) \in \Pi$, a redistribution $\varphi(I, P, \mathbf{x}) \in R(I, P, \mathbf{x})$. Given rule φ and $(I, P, \mathbf{x})$, we denote by $\varphi_i(I, P, \mathbf{x})$ the redistribution of individual i.

4.3.2 | Axioms

We now consider four axioms for rebate rules.

The first axiom reflects a standard fairness principle. It states that if two agents contribute the same amount, they must receive identical redistributions.

Equal Treatment of Equals (ETE). A rule rule φ satisfies (ETE) if for each problem $(I, P, \mathbf{x}) \in \Pi$, for all individuals $i, j \in I$ such that $x_i = x_j$, we have $\varphi_i(I, P, \mathbf{x}) = \varphi_j(I, P, \mathbf{x})$.

The second axiom guarantees that increasing one's contribution does not put the contributor at a disadvantage. Specifically, if an individual increases their contribution, either a more

---

[4] We assume that the funded alternative is the most expensive one among those whose cost does not exceed the total amount collected. While this ensures that lower-cost alternatives could be incorporated as part of the project's progression, they become less relevant since the focus shifts to financing the most advanced alternative achievable given the available contributions.

expensive project alternative is funded, or their redistribution amount increases by at least the additional contribution.[5]

Contribution Monotonicity (CM). A rule φ satisfies (CM) if, for each problem $(I, P, \mathbf{x}) \in \Pi$, with P_k being the funded alternative, the following holds:

For each $i \in I$ such that $x_i \geq \bar{c}_k$,[6] if the contribution of agent i increases to $x_i' > x_i$, then either

$$\varphi_i(I, P, (\mathbf{x}_{-i}, x_i')) - \varphi_i(I, P, \mathbf{x}) \geq x_i' - x_i,$$

or

$$x_i' + \sum_{j \in I \setminus \{i\}} x_j \geq c_{k'} \text{ with } k' > k.$$

The third axiom ensures that if an individual benefits from redistribution, then she continues to receive a positive redistribution when new contributors join the population.

Consistency (C). A rule φ satisfies (C) if, for each problem $(I, P, \mathbf{x}) \in \Pi$ and for any partition $\mathcal{P} = \{I', I''\}$ of I such that $I' \cup I'' = I$ and $I' \cap I'' = \emptyset$:

$$\forall i \in I', \varphi_i(I', P, \mathbf{x}') > 0 \Rightarrow \varphi_i(I, P, \mathbf{x}) > 0, \text{ and } \forall i \in I'', \varphi_i(I'', P, \mathbf{x}'') > 0 \Rightarrow \varphi_i(I, P, \mathbf{x}) > 0,$$

where $\mathbf{x}' \equiv (x_i)_{i \in I'}$ and $\mathbf{x}'' \equiv (x_i)_{i \in I''}$.

This ensures that an agent's redistribution does not become null solely due to the addition of new contributors. As discussed in the introduction, this axiom is crucial for encouraging broad participation.

The fourth axiom ensures that whenever there is a positive surplus, at least part of it must be redistributed.

Partial Surplus Redistribution (PSR). A rule φ satisfies (PSR) if, for each problem $(I, P, \mathbf{x}) \in \Pi$, $S > 0$ implies that there exists $i \in I$ such that $\varphi_i(I, P, \mathbf{x}) > 0$.

For the last two axioms, we consider stronger versions of each. The first requires that when the population is expanded, individuals must receive at least the same redistribution as before.

Strong-Consistency (Strong-C). A rule φ satisfies (Strong-C) if, for each problem $(I, P, \mathbf{x}) \in \Pi$, and for any partition $\mathcal{P} = \{I', I''\}$ of I such that $I' \cup I'' = I$ and $I' \cap I'' = \emptyset$:

$$\forall i \in I', \varphi_i(I, P, \mathbf{x}) \geq \varphi_i(I', P, \mathbf{x}'), \text{ and } \forall i \in I'', \varphi_i(I, P, \mathbf{x}) \geq \varphi(I'', P, \mathbf{x}''),$$

where $\mathbf{x}' \equiv (x_i)_{i \in I'}$ and $\mathbf{x}'' \equiv (x_i)_{i \in I''}$.

The second axiom ensures that the entire surplus is redistributed.

Full Surplus Redistribution (FSR). A rule φ satisfies (FSR) if, for each problem $(I, P, \mathbf{x}) \in \Pi$, $\sum_{i \in I} \varphi_i(I, P, \mathbf{x}) = S$.

---

[5] Bagnoli and Lipman (1989) suggest that rebate rules should have the property that an increase in the contribution of \$1 by individual i should not generate a rebate to individual i of more than \$1. We formalize this reasoning in more detail in Section 4.6.

[6] We rely on the project's average cost as a benchmark to capture sufficiently high individual contributions, while imposing no constraint when contributions are below this threshold.

4.4 | Limits on Rebate Rules

In this section, we highlight the main limitations regarding the compatibility of the axioms presented in the previous section with rebate rules. Our first result establishes a fundamental limitation regarding incentive compatibility and equal treatment.

Theorem 1. There is no rule φ that satisfies Equal Treatment of Equals (ETE) and Contribution Monotonicity (CM).

Proof. See Appendix C.2.1. ■

The implication of Theorem 1 is that ensuring equal treatment requires redistributing part of any additional contribution to others. In practice, this weakens individual incentives to contribute, as they anticipate that a share of their increased contribution will neither be returned to them nor directly benefit the project.

As discussed in the introduction, redistribution is absent in many crowdfunding mechanisms. The following definition formalizes the *Null Rebate* rule.

Definition 1. (Null Rebate rule) The Null Rebate rule φ^0 is defined for each $(I, P, \mathbf{x}) \in \Pi$ as:

$$\forall i \in I, \varphi_i^0(I, P, \mathbf{x}) = 0.$$

In other words, φ^0 specifies that the surplus is not redistributed to the participants. Our first result establishes a limitation on surplus redistribution when (ETE) and (C) are required.

Theorem 2. A rule φ satisfies Equal treatment of equals (ETE) and Consistency (C) if, and only if, $\varphi = \varphi^0$.

Proof. See Appendix C.2.2. ■

Theorem 2 is insightful because it shows that designing a rule that respects both (ETE), a fundamental axiom of fairness, and (C), which guarantees redistribution when individuals are added, is only possible if no surplus is redistributed. In the context of crowdfunding, Theorem 2 implies that if a positive redistribution is desired by adding contributors, it is not possible to treat them equally. Our next result further extends this limitation.

Theorem 3. There is no rule φ that satisfies Consistency (C) and Partial Surplus Redistribution (PSR).

Proof. See Appendix C.2.3. ■

The intuition behind this impossibility stems from the nature of alternative funding. When contributions are added, a project (or a more expensive alternative) is funded, which reduces the available surplus. As a result, it becomes impossible to have a partial redistribution for individuals, and the addition of new individuals leads to a zero surplus. Figure 4.1 illustrates this phenomenon.

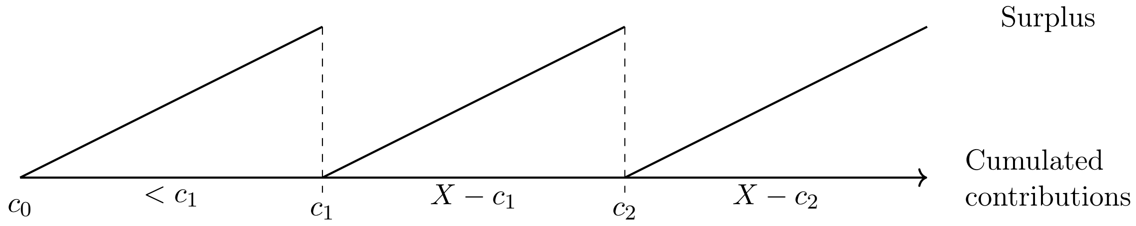


Figure 4.1: Illustration of Available Surplus

We conclude this section by restricting the considered domain. Given a problem $(I, P, \mathbf{x}) \in \Pi$, we say that *a rule* φ *satisfies* Strong-Consistency (Strong-C) *in* $(I, P, \mathbf{x})$ if for any partition $\mathcal{P} = \{I', I''\}$ of I such that $I' \cup I'' = I$ and $I' \cap I'' = \emptyset$:

$$\forall i \in I', \varphi_i(I, P, \mathbf{x}) \geq \varphi_i(I', P, \mathbf{x}'), \text{ and } \forall i \in I'', \varphi_i(I, P, \mathbf{x}) \geq \varphi(I'', P, \mathbf{x}''),$$

where $\mathbf{x}' \equiv (x_i)_{i \in I'}$ and $\mathbf{x}'' \equiv (x_i)_{i \in I''}$.

Similarly, given a problem $(I, P, \mathbf{x}) \in \Pi$,*a rule* φ *satisfies* Full Surplus Redistribution (FSR) in $(I, P, \mathbf{x})$ if $\sum_{i \in I} \varphi_i(I, P, \mathbf{x}) = S$.

Theorem 4. Consider a problem $(I, P, \mathbf{x})$ such that for each $i \in I, x_i < c_1$. If a rule satisfies Strong-Consistency (Strong-C) and Full Surplus Redistribution (FSR) in $(I, P, \mathbf{x})$, then there is no funded project.

Proof. See Appendix C.2.4. ■

In practice, the condition imposed by Theorem 4 holds in many problems, where no individual contributes more than the cost of the first project alternative. If this condition is not met, the first project alternative is funded by a single agent. The implication of Theorem 4 is that the only solution to achieve full surplus redistribution, ensuring independence from population size, is if no project is funded.

4.5 | Proportional Rebate with Threshold Rule and Axioms

In this section, we introduce a rebate rule designed to address the limitations discussed in the previous section, while aiming to satisfy key axioms essential to crowdfunding mechanisms. Specifically, if no project is funded, participants receive a full refund of their contributions,[7] and if there is no surplus, no redistribution occurs. Our rule guarantees both of these fundamental conditions. The *Proportional Rebate with Threshold* (PRT) rule operates based on the project's average cost, ensuring that any redistribution leads to a final payment that converges to the project's average cost. Before defining the PRT rule, we introduce two new notations. Let $\hat{X} \equiv \sum_{j \in \{j \in I: x_j > \bar{c}_{k^*}\}} (x_j - \bar{c}_{k^*})$, and $\check{X} \equiv \sum_{j \in \{j \in I: x_j \leq \bar{c}_{k^*}\}} (\bar{c}_{k^*} - x_j)$ where Pk^*

---

[7] This property aligns with the AoN crowdfunding mechanism.

is the project alternative funded.[8] Intuitively, $\hat{X}$ represents the total excess contributions above the project's average cost, while $\check{X}$ captures the total shortfall of contributions below this threshold.

Definition 2. (Proportional Rebate with Threshold rule). The rule ψ is defined, for each $(I, P, \mathbf{x}) \in \Pi$, with P_{k^*} being the funded project alternative, as for each $i \in I$,

$$\psi_i(I, P, \mathbf{x}) = \begin{cases} (x_i - \bar{c}_{k^*}) - \frac{x_i - \bar{c}_{k^*}}{\hat{X}} \times \check{X} & \text{if } x_i > \bar{c}_{k^*}, \\ 0 & \text{otherwise.} \end{cases}$$

The rule ψ redistributes the surplus based on how each individual's contribution compares to the project's average cost. Participants who contribute more than the average cost receive a proportional rebate based on the excess contribution. Those whose contributions are below the average cost do not receive any redistribution. This rule adjusts the final payments according to each individual's contribution relative to the overall funding, while encouraging greater participation by offering a clear proportional rebate based on the project's success. We formally demonstrate this in the remainder of this section.

Given the impossibilities presented in Theorems 1 and 3, we propose weakened axioms to address these challenges. The first of these is a weakened form of consistency. This axiom requires that when individuals are added to the population, the redistribution either remains positive or allows for the financing of a project (or a more costly alternative).

Weak-Consistency (Weak-C) A rule φ satisfies (Weak-C) if, for each problem $(I, P, \mathbf{x}) \in \Pi$, and for any partition $\mathcal{P} = \{I', I''\}$ of I such that $I' \cup I'' = I$ and $I' \cap I'' = \emptyset$, with $\varphi(I', P, \mathbf{x}')$ with project alternative $P_{k'}$ funded, $\varphi(I'', P, \mathbf{x}'')$ with project alternative $P_{k''}$ funded, and $\varphi(I, P, \mathbf{x})$ with project alternative P_k funded, then the following conditions hold:

$$\forall i \in I', \varphi_i(I', P, \mathbf{x}') > 0 \Rightarrow \varphi_i(I, P, \mathbf{x}) > 0, \text{ or } k > k',$$

and,

$$\forall i \in I'', \varphi_i(I'', P, \mathbf{x}'') > 0 \Rightarrow \varphi_i(I, P, \mathbf{x}) > 0 \text{ or } k > k'',$$

where $\mathbf{x}' \equiv (x_i)_{i \in I'}$ and $\mathbf{x}'' \equiv (x_i)_{i \in I''}$.[9]

The second weakened axiom addresses the monotonicity of an individual's redistribution in relation to their contribution. Specifically, it ensures that if an individual who has contributed more than the average cost of the funded project alternative increases their contribution, their redistribution will increase by at least a portion of that increase, or a better alternative will be funded. To formalize this, we consider the sum of the excess contributions from all individuals other than i, that is, $\hat{X}_{-i} \equiv \sum_{j \in \{j \in I \setminus \{i\} : x_j > \bar{c}_{k^*}\}} (x_j - \bar{c}_{k^*})$.

Weak-Contribution Monotonicity (Weak-CM). A rule φ satisfies (Weak-CM) if, for each problem $(I, P, \mathbf{x}) \in \Pi$, with P_k being the funded project alternative the following holds:

---

[8] Note that we have $S = \hat{X} + \check{X}$.

[9] (Weak-C) is particularly relevant in the context of public good provision involving multiple municipalities. For instance, two neighboring towns aiming to build a public swimming facility can pool their contributions to fund a larger, improved alternative. Otherwise, any excess contributions are returned to them.

For each $i \in I$ such that $x_i \geq \bar{c}_k$, if the contribution of agent i increases to $x'_i > x_i$, then either

$$\varphi_i(I, P, (\mathbf{x}_{-i}, x'_i)) - \varphi_i(I, P, \mathbf{x}) \geq (x'_i - x_i) \times \left(1 - \frac{\check{X} \times \hat{X}_{-i}}{\left(\hat{X}_{-i} + x'_i - \bar{c}_{k^*}\right) \times \left(\hat{X}_{-i} + x_i - \bar{c}_{k^*}\right)}\right),$$

or

$$x'_i + \sum_{j \in I \setminus \{i\}} x_j \geq c_{k'} \text{ with } k' > k.$$

Note that the definition of (Weak-CM) uses the notations introduced in the PRT Rule. The underlying rationale is that the redistribution must be a function of the individual's initial contribution, their increased contribution, and the contributions of other participants.

Before introducing our main result for this section, we define a new axiom. A desirable axiom in the context of redistribution is that an individual who contributes more should not end up with a lower net payment than someone who contributed less. This axiom serves two purposes. First, it ensures fairness, as redistributions should not result in those who contribute more receiving less than those who contribute less. Second, it limits the possibility of manipulation, ensuring that contributing more does not lead to a greater redistribution that ultimately reduces the individual's effective contribution.

Monotonicity of Net Payment (MNP). A rule φ satisfies (MNP) if, for each problem $(I, P, \mathbf{x}) \in \Pi$, for each $i, j \in I$ such that $x_i \geq x_j$, then $x_i - \varphi_i(I, P, \mathbf{x}) \geq x_j - \varphi_j(I, P, \mathbf{x})$.

Our next result demonstrates that the rule ψ satisfies the desired axioms.

Theorem 5. Rule ψ satisfies Equal Treatment of Equals (ETE), Full Surplus Redistribution (FSR), Monotonicity of Net Payment (MNP), Weak-Consistency (Weak-C) and Weak-Contribution Monotonicity (Weak-CM).

Proof. See Appendix C.2.5 ■

Theorem 5 establishes that the rule ψ adheres to the key axioms related to fairness, incentives to contribute, and the capacity to increase the number of contributors. The following proposition provides further insight into the incentives to contribute when all participants contribute more than the average cost of the project, by redistributing the entire additional contribution.

Proposition 1. Consider a problem $(I, P, \mathbf{x})$ such that P_k is funded. If for each $i \in I$, $x_i \geq \bar{c}_k$, then for each $i \in I$, $\psi_i(I, P, \mathbf{x}) = x_i - \bar{c}_k$.

Proposition 1 suggests that after redistribution, all individuals contribute the same amount to the project, with the contribution of each individual being reduced accordingly.[10]

---

[10] The proof is straightforward since $\check{X}$ is equal to 0, and is therefore omitted.

4.6 | Comparison of Rebate Rules

In this section, we evaluate how different rules affect an individual's redistribution when they increase their contribution. As shown in the proof of Theorem 5, an increase in an individual's contribution always leads to the same share of the redistribution,[11] or the financing of a more costly project alternative. To quantify this effect, we define the *Marginal Rebate of Contribution* (MRC) as the rate of change in an individual's rebate with respect to their own contribution, while keeping others' contributions fixed.

Definition 3. Given a rule φ, the Marginal Rebate of Contribution (MRC) of an individual i when their contribution increases from x_i to x'_i is defined as:

$$MRC(\varphi_i(I, P, \mathbf{x}), x'_i) = \frac{\varphi_i(I, P, (\mathbf{x}_{-i}, x'_i)) - \varphi_i(I, P, \mathbf{x})}{x'_i - x_i}.$$

The underlying argument is that the greater the increase in redistribution in response to higher contributions, the more individuals will be incentivized to contribute.[12] We now introduce two commonly used rebate rules: the Shapley rule and the Proportional Rebate (PR) rule.

Definition 4. (Shapley rule) The rule φ^S is defined for each $(I, P, \mathbf{x}) \in \Pi$, with P_{k^*} being the funded project alternative as:

$$\forall i \in I, \varphi_i^S(I, P, \mathbf{x}) = \sum_{T \subseteq I \setminus \{i\}} \frac{|T|!(|I| - |T| - 1)!}{|I|!} \left(v(T \cup \{i\}) - v(T)\right),$$

where $v(T) = \max\left\{0,\ \sum_{j \in T} x_j - c_{k^*}\right\}$ represents the surplus that coalition T would generate relative to the cost c_{k^*} of the funded project alternative.

The φ^S rule is based on the Shapley value, which is widely studied in the fair division literature.

Definition 5. (Proportional Rebate rule). The rule φ^P is defined for each $(I, P, \mathbf{x}) \in \Pi$, with P_{k^*} being the funded project alternative, as:

$$\forall i \in I, \varphi_i^P(I, P, \mathbf{x}) = \frac{x_i}{X} \times S.$$

Although the underlying argument behind φ^P and ψ is similar, the implementation of a threshold significantly influences the resulting redistributions. In φ^P, the redistribution is proportional for all individuals, whereas in ψ, only individuals who have contributed more than the average cost are considered in the redistribution. Notably, this redistribution is consequently lower when the contributions of individuals increase.

---

[11] This share corresponds to $\left(1 - \frac{\check{X} \times \hat{X}_{-i}}{(\hat{X}_{-i} + x'_i - \bar{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \bar{c}_{k^*})}\right)$.

[12] Note that the MRC corresponds to the partial derivative of the rebate rule when the increase in individual i's contribution, namely $x'_i - x_i$, approaches 0.

Proposition 2. Shapley rule and Proportional Rebate rule do not satisfy Weak-Contribution Monotonicity (Weak-CM).

The consequence of Proposition 2 is that, when using rules φ^S and φ^P, a larger portion of the increase in individual contributions will be redistributed to others compared to rule ψ. To illustrate this phenomenon, consider the following examples.

Example 1. Consider a problem $(I, P, \mathbf{x})$ where $I = \{i_1, i_2, i_3\}$, $P = \{P_0, P_1\}$ with $c_1 = 12$, it follows that $\bar{c}_1 = 4$. Suppose $x_{i_1} = 7$, $x_{i_2} = 8$, $x_{i_3} = 4$ and $x'_{i_1} = 8$. Table 4.1 illustrates the redistributions for each rule.

Table 4.1: Comparison of redistribution outcomes under different rules for Case 1

Redistribution	**PRT**		**Shapley**		**PR**	
x_{i_1}	7	8	7	8	7	8
r_{i_1}	3	4	2.83	3.33	2.58	3.2
r_{i_2}	4	4	2.83	3.33	2.95	3.2
r_{i_3}	0	0	1.33	1.33	1.47	1.6
Fix values		$x_{i_2} = 8$	$x_{i_3} = 4$	$c_1 = 12$	$\bar{c}_1 = 4$	

(Notes. Comparison of redistribution outcomes under different rules (PRT, Shapley, and PR) for Case 1 without compensating burden (everyone contributes at least the average cost $\bar{c}_1 = 4$). The table presents the redistribution amounts $(r_{i_1}, r_{i_2}, r_{i_3})$ for different initial contributions x_{i_1} (7 and 8), given fixed values of $x_{i_2} = 8$, $x_{i_3} = 4$, total cost $c_1 = 12$, and average cost $\bar{c}_1 = 4$.)

In this example, when i_1's contribution increases from 7 to 8, the MRC values for i_1 under each rule are:

- $MRC(\psi_i(I, P, \mathbf{x}), 8) = 1$,
- $MRC(\varphi_i^S(I, P, \mathbf{x}), 8) = 0.50$, and
- $MRC(\varphi_i^P(I, P, \mathbf{x}), 8) = 0.62$.

This example is fully detailed in Figure 4.2, where the variation in i_1's contribution corresponds to Case 1. In this case, the contributions of i_2 and i_3 are sufficient to fund the project, meaning there is no burden. The following table further demonstrates that this observation holds even when accounting for the burden.

We consider another example where the contributions of i_2 and i_3 differ, with $x_{i_2} = 7$ and $x_{i_3} = 2$. Table 4.2 shows that when i_1's contribution increases from 7 to 8, the MRC values for i_1 under each rule are:

- $MRC(\psi_i(I, P, \mathbf{x}), 8) = 0.86$,
- $MRC(\varphi_i^S(I, P, \mathbf{x}), 8) = 0.50$, and
- $MRC(\varphi_i^P(I, P, \mathbf{x}), 8) = 0.60$.

Table 4.2: Comparison of redistribution outcomes under different rules for Case 2

Redistribution	**PRT**		**Shapley**		**PR**	
x_{i_1}	7	8	7	8	7	8
r_{i_1}	2	2.86	1.67	2.17	1.75	2.35
r_{i_2}	2	2.14	1.67	2.17	1.75	2.06
r_{i_3}	0	0	0.67	0.67	0.50	0.59
Fix values		$x_{i_2} = 7$	$x_{i_3} = 2$	$c_1 = 12$	$\bar{c}_1 = 4$	

(*Notes.*Comparison of redistribution outcomes under different rules (PRT, Shapley, and PR) for Case 2 with compensating burden (someone contributes less than the average cost $\bar{c}_1 = 4$). The table presents the redistribution amounts $(r_{i_1}, r_{i_2}, r_{i_3})$ for different initial contributions x_{i_1} (7 and 8), given fixed values of $x_{i_2} = 7$, $x_{i_3} = 2$, total cost $c_1 = 12$, and average cost $\bar{c}_1 = 4$.)

The reasoning behind this observation is that a larger portion of i_1's additional contribution is redistributed to the other individuals. Specifically, the amount redistributed to i_2 is due to i_3's contribution being lower than $\bar{c}_1$. These values correspond to Case 2 in Figure 4.2.

Figure 4.2 illustrates the redistribution outcomes of the three rules considered in this section across five distinct cases. These cases vary individual contributions while keeping the total cost $c_1 = 12$ and the average cost $\bar{c}_1 = 4$ constant. The key distinction among them lies in how individual contributions compare to the average cost. By systematically adjusting this relationship, each scenario highlights a fundamental aspect of the redistribution rules. Additional cardinal combinations would merely interpolate among these representative cases, adding minimal incremental insight, as the essential characteristics of the redistribution outcomes have already been captured.

A general observation is that the PRT rule yields the highest MRC values when the initial contribution exceeds the average cost threshold $\bar{c}_1$, prioritizing over-contributors in the surplus allocation. The direct comparison for Case 1 and Case 3 is shown in Figure 4.3, while the direct comparison for Case 2, Case 4, and Case 5 is presented in Figure C.1 (Appendix C.1).

Case 1 presents a scenario in which one contributor provides a higher contribution ($x_{i_2} = 8 > \bar{c}_1$) while the other contributes exactly at the threshold ($x_{i_3} = 4 = \bar{c}_1$), with their combined contribution exactly covering the project cost ($x_{i_2} + x_{i_3} = 12 = c_1$).

Here, the PRT rule exhibits a fundamental distinction: contributors whose contributions exceed $\bar{c}_1$ do not receive the full surplus, as part of it is used to compensate for contributions below the project's average cost. Consequently, their rebate under the rule ψ does not grow linearly.

Case 2 involves one contribution below $\bar{c}_1$ ($x_{i_3} = 2 < \bar{c}_1$) while the other exceeds it ($x_{i_2} = 7 > \bar{c}_1$). Yet the total contribution is insufficient to cover the cost ($x_{i_2} + x_{i_3} = 9 < c_1$). This case stands out in terms of the redistribution obtained under the PRT rule. As long as x_{i_1} remains below $\bar{c}_1$, $\psi_{i_2}(I, P, \mathbf{x})$ increases linearly. However, once x_{i_1} exceeds

$\bar{c}_1$, i_1 and i_2 proportionally share the shortfall from i_3's contribution, leading to a non-linear redistribution pattern. This effect arises because, beyond $\bar{c}_1$, the higher contributors collectively absorb the deficit of the lower contributor.

In Case 3, both contributors provide contributions below $\bar{c}_1$ ($x_{i_2} = 3 < \bar{c}_1$, $x_{i_3} = 2 < \bar{c}_1$), with their total contribution remaining insufficient ($x_{i_2} + x_{i_3} = 5 < c_1$). Once the funding goal is reached, the PRT rule exhibits a significantly steeper slope compared to both the Shapley rule and the PR rule.

In Case 4, the contribution of i_2 and i_3 exceed the average cost ($x_{i_2} = 7 > \bar{c}_1$, $x_{i_3} = 6 > \bar{c}_1$), and their total contribution surpasses the required cost ($x_{i_2} + x_{i_3} = 13 > c_1$). Under these conditions, the PRT rule grants linearly increasing rebates only after the threshold $\bar{c}_1$ is exceeded. In contrast, both the Shapley rule and the PR rule provide rebates from the very first unit of contribution. The Shapley rule redistributes the surplus according to marginal contributions, leading to moderate rebates across contributors. The PR rule, in contrast, distributes the surplus proportionally among all contributors, resulting in smaller but more evenly allocated rebates.

Finally, in Case 5, where both contributions exceed $\bar{c}_1$ ($x_{i_2} = 6 > \bar{c}_1$, $x_{i_3} = 5 > \bar{c}_1$) but their combined contribution is insufficient to meet the required funding level ($x_{i_2}+x_{i_3} = 11 < c_1$), all three rules result in a full refund of contributions. However, an important distinction arises when the total contribution surpasses the required cost: the PRT rule ensures that contributors with contributions below $\bar{c}_1$ receive no rebate, whereas the Shapley rule and PR rule provide rebates, independent of whether individual contributions exceed $\bar{c}_1$.

These observations indicate that the PRT rule leads to a greater increase in the redistribution received by an individual who raises their contribution, provided that the contribution exceeds $\bar{c}_1$. The PRT rule drives final payments closer to the project's average cost when the initial contribution surpasses this threshold. By contrast, the Shapley rule allocates redistribution based on an individual's importance in the project's completion, thereby rebating according to systemic importance rather than overcontribution. Meanwhile, the PR rule results in a more moderate increase in the redistribution received by an individual, as a significant portion of their additional contribution is redistributed to other contributors.

These observations suggest that the PRT rule effectively mitigates overpayment concerns while ensuring that high contributors receive proportionate redistribution. This makes it a robust alternative for surplus redistribution in crowdfunding mechanisms and other collective funding environments, where incentivizing large contributions while maintaining fairness is a key policy objective.

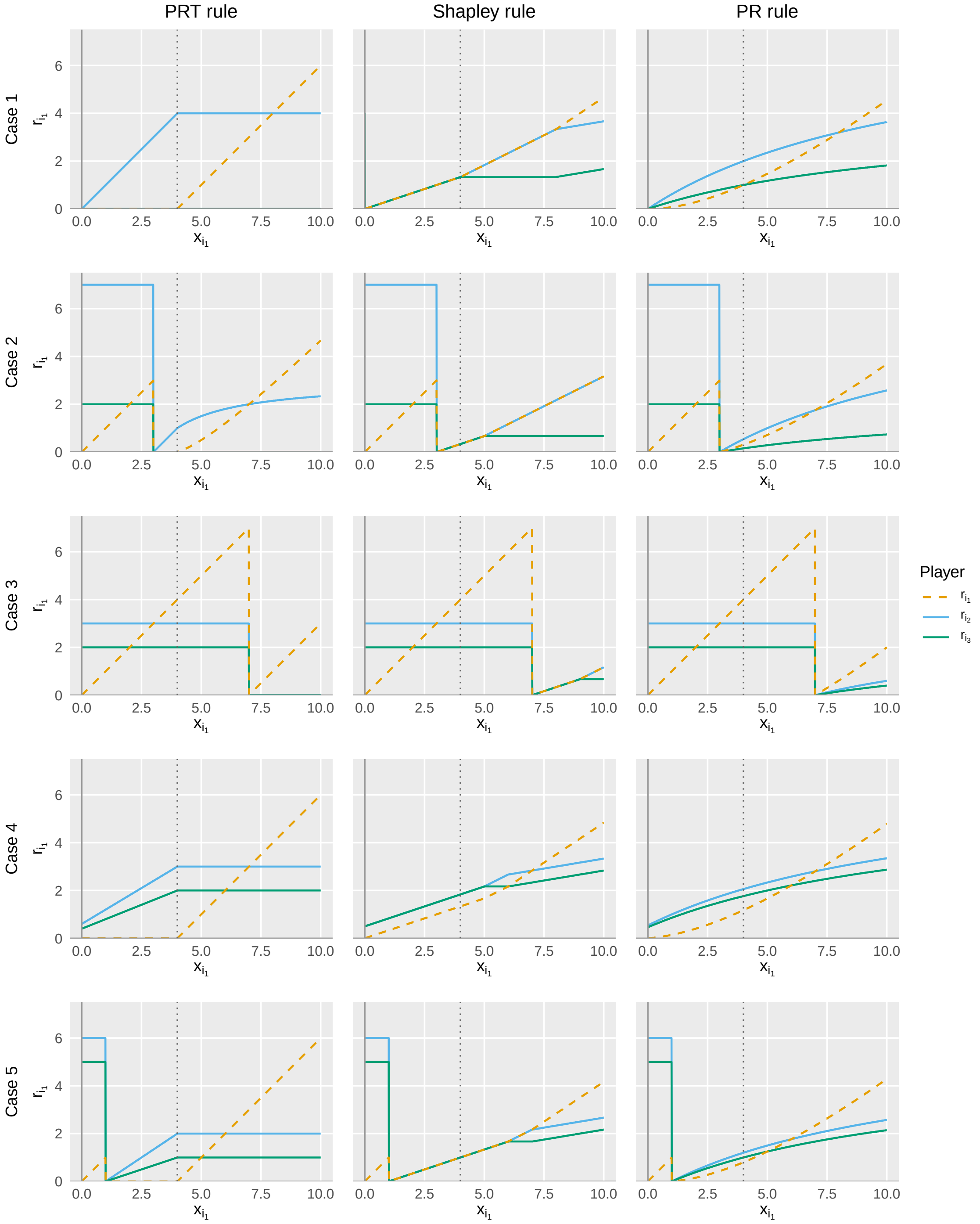


Figure 4.2: The figure presents redistribution outcomes r_i across the five cases (rows) with individual contributions x_{i_1} on the horizontal axis. In each case, x_{i_2} and x_{i_3} are fixed, while the average cost $\bar{c}_1$ remained constant. The three columns represent the rebate rules: PRT, Shapley, and PR.

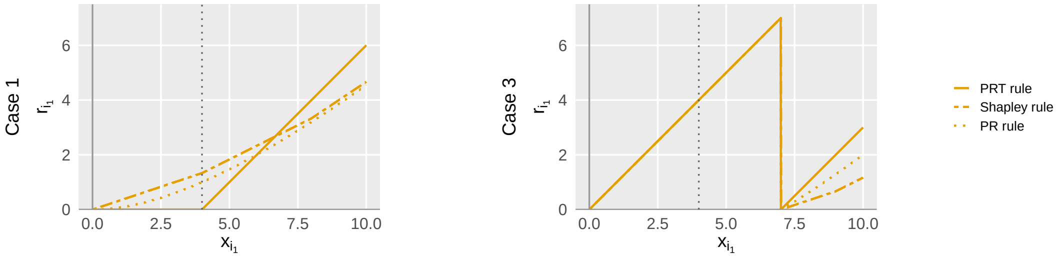


Figure 4.3: The figure presents the redistribution outcomes r_{i_1} across Case 1 and Case 3, with individual contributions x_{i_1} on the horizontal axis. Each plot represents the three rebate rules: PRT (solid line), Shapley (two-dash line), and PR (dotted line).

4.7 | Concluding Remarks

In this paper, we define surplus redistribution problems in crowdfunding mechanisms and adopt an axiomatic approach. We identify fundamental limitations in the design of rebate rules by demonstrating the impossibility of simultaneously satisfying participation incentives, contribution incentives, and a fairness criterion. To address these constraints, we propose the Proportional Rebate with Threshold rule. Beyond satisfying a weaker version of these axioms—Weak-Consistency (Weak-C) and Weak-Contribution Monotonicity (Weak-CM)—this rule also satisfies Equal Treatment of Equals (ETE), Full Surplus Redistribution (FSR), Monotonicity of Net Payment (MNP). We show that this rule leads to higher redistribution compared to commonly used rebate rules when an individual increases their contribution. We argue that this property strengthens incentives to contribute.

While crowdfunding mechanisms aim to ensure efficiency in public goods provision,[13] they often lack structured rebate rules. The PRT rule addresses this issue by offering a systematic approach to surplus redistribution, making it more suitable for crowdfunding and voluntary public goods funding.

Future research could examine the experimental validation of contribution incentives under different rebate rules. Theoretical studies may also explore the role of information in this context. Rondeau et al. (1999) notably shows that withholding information about provision costs leads to contributions that better reflect individuals' true valuations.

---

[13] A public good is efficiently provided if aggregate contributions meet or exceed the provision point (see Rondeau et al., 1999).

Appendix | C

Designing Rebate Rules in Public Goods Provision

Appendix

C.1 | Additional Analysis

In this section, we provide additional analysis for the remaining three cases not covered in Section 4.6.

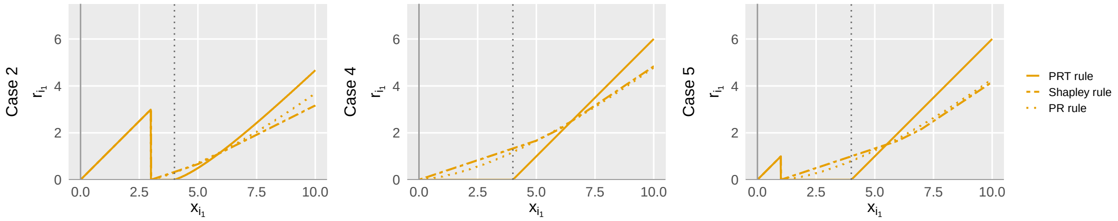


Figure C.1: The figure presents the redistribution outcomes r_{i_1} across Case 2, Case 4 and Case 5, with individual contributions x_{i_1} on the horizontal axis. Each plot represents the three rebate rules: PRT (solid line), Shapley (two-dash lines), and PR (dotted line).

Case 2, where one contribution is below $\bar{c}_1$ and the other above it, but the total remains insufficient ($x_{i_2}+x_{i_3} < c_1$), illustrates a key feature of the PRT rule: Once contributions exceed $\bar{c}_1$, rebates grow non-linearly, following the argument presented in Section 4.6—higher contributors collectively absorb the deficit of the lower contributor.

In Case 4, where both contributors exceed the average cost ($x_{i_2} > \bar{c}_1, x_{i_3} > \bar{c}_1$) and their combined contribution exceeds the required cost ($x_{i_2} + x_{i_3} > c_1$), the redistribution differ across rules. The PRT rule grants rebates only after contributions exceed $\bar{c}_1$, with a diminishing MRC.

In contrast, the Shapley rule redistributes surplus based on marginal contributions, leading to moderate rebates, while the PR rule distributes the surplus proportionally, resulting in an increase in redistributions for all contributors.

In Case 5, where both contributors exceed $\bar{c}_1$ but their total contribution falls short ($x_{i_2} + x_{i_3} < c_1$), all three rules fully refund contributions. However, when the threshold is met, the PRT rule does not rebate contributors below $\bar{c}_1$, unlike the Shapley rule and PR rule, which redistribute surplus without considering this contribution threshold.

C.2 | Proofs

C.2.1 | Proof of Theorem 1

Proof. We prove Theorem 1 by means of an example. Consider a problem where $I = \{i_1, i_2\}$, $P = \{P_0, P_1\}$, and c_1 with $x_{i_1} < \frac{c_1}{2}$ and $x'_{i_1} = x_{i_2} > \frac{c_1}{2}$ with $x_{i_1} + x_{i_2} > c_1$. Suppose φ satisfies (ETE), and (CM). Consider $(I, P, (x'_{i_1}, x_{i_2}))$, we have $S = 2 \times x_{i_2} - c_1$. Since φ satisfies (CM) we know that $\varphi_{i_1}(I, P, (x'_{i_1}, x_{i_2})) - \varphi_{i_1}(I, P, \mathbf{x}) \geq x_{i_2} - x_{i_1}$, meaning that $\varphi_{i_1}(I, P, (x'_{i_1}, x_{i_2})) \geq x_{i_2} - x_{i_1}$. Since φ satisfies (ETE), we know that $\varphi_{i_1}(I, P, (x'_{i_1}, x_{i_2})) = \varphi_{i_2}(I, P, (x'_{i_1}, x_{i_2}))$. Therefore, we know that $\varphi_{i_2}(I, P, (x'_{i_1}, x_{i_2})) \geq x_{i_2} - x_{i_1}$. We have $\varphi_{i_1}(I, P, (x'_{i_1}, x_{i_2})) + \varphi_{i_2}(I, P, (x'_{i_1}, x_{i_2})) \geq 2 \times x_{i_2} - 2 \times x_{i_1}$, which is a contradiction since $S = 2 \times x_{i_2} - c_1 < 2 \times x_{i_2} - 2 \times x_{i_1}$, as $x_{i_1} < \frac{c_1}{2}$. ■

C.2.2 | Proof of Theorem 2

Proof. **Existence:** φ_0 satisfies (ETE) and (C).
We know that for each $i \in I$, $r_i = 0$. Consider $(I, P, \mathbf{x})$ with $i, j \in I$ such that $i \neq j$ and $x_i = x_j$. It is direct that φ^0 satisfies (ETE) since $\varphi^0_i(I, P, \mathbf{x}) = \varphi^0_j(I, P, \mathbf{x}) = 0$. Similarly, for any partition $\mathcal{P}$ over I such that $\mathcal{P} = \{I', I''\}$, it holds that for each $i \in I'$, $\varphi^0_i(I, P, \mathbf{x}) \geq \varphi^0_i(I', P, (x_i)) = 0$ and for each $i \in I''$, $\varphi^0_j(I, P, \mathbf{x}) \geq \varphi^0_j(I'', P, (x_j)) = 0$.
Uniqueness: If a rule satisfies (ETE) and (C), then it has to be φ_0.
By contradiction, suppose there exists a rule φ that satisfies (ETE) and (C) such that $\varphi \neq \varphi_0$. Since $\varphi \neq \varphi_0$, for some problem $(I, P, \mathbf{x})$, there exists $i \in I$ such that $\varphi_i(I, P, \mathbf{x}) > 0$. Theorem 3 implies that there is no rule such that $\varphi_i(I, P, \mathbf{x}) > 0$ for some $i \in I$, that satisfies (ETE) and (C). This concludes the proof. ■

C.2.3 | Proof of Theorem 3

Proof. We prove Theorem 3 by means of an example. Consider a problem where $I = \{i_1, i_2\}$, $P = \{P_0, P_1\}$, $x_{i_1} > 0, x_{i_2} > 0$ and $c_1 = x_{i_1} + x_{i_2}$. Let $I' = \{i_1\}$ and $I'' = \{i_2\}$.
Suppose φ satisfies (C) and (PSR). Consider $\varphi(I', P, (x_{i_1}))$. We know that $c_1 > x_{i_1} > 0$ and as φ satisfies (PSR), we have that $\varphi_{i_1}(I', P, (x_{i_1})) > 0$. Similarly, $\varphi(I'', P, (x_{i_2}))$, we have $c_1 > x_{i_2} > 0$ and, by (PSR), $\varphi_{i_2}(I'', P, (x_{i_2})) > 0$.
Now consider $\varphi(I'', P, \mathbf{x})$. Since $c_1 = x_{i_1} + x_{i_2}$, project alternative P_1 is realized and $S = (x_{i_1} + x_{i_2}) - c_1 = 0$. Then, $\varphi_{i_1}(I'', P, \mathbf{x}) = \varphi_{i_2}(I'', P, \mathbf{x}) = 0$. We therefore have $\varphi_{i_1}(I'', P, \mathbf{x}) \not> 0$ and $\varphi_{i_2}(I'', P, \mathbf{x}) \not> 0$ which contradict that φ satisfies (C). ■

C.2.4 | Proof of Theorem 4

Proof. By contradiction, suppose there exists a rule φ that satisfies (Strong-C) and (FSR) in a problem $(I, P, \mathbf{x})$ where for each $i \in I, x_i < c_1$, and a project alternative $P_k \neq P_0$ is funded. We know that $c_k > 0$, therefore, $X - c_k < X$, meaning that there exists $i \in I$ such that $x_i > \varphi_i(I, P, \mathbf{x})$. Without loss of generality, consider a partition such that $I' = \{i\}$

and $I'' = I \setminus I'$. Since $x_i < c_1$, and φ satisfies (FSR), we know that $\varphi_i(I', P, (x_i)) = x_i$. Therefore, $\varphi_i(I', P, (x_i)) > \varphi_i(I, P, \mathbf{x})$, leading to a contradiction. ■

C.2.5 | Proof of Theorem 5

Proof. Fix an arbitrary problem $(I, P, \mathbf{x})$ and let P_{k^*} be the funded project alternative.

- ψ satisfies Equal Treatment of Equals (ETE).

Let $i, j \in I$ such that $x_i = x_j$. If $S = 0$, we know that $\psi_i(I, P, \mathbf{x}) = \psi_j(I, P, \mathbf{x}) = 0$. Similarly, if $x_i \leq \bar{c}_{k^*}$, we have $\psi_i(I, P, \mathbf{x}) = \psi_j(I, P, \mathbf{x}) = 0$. Finally, if $x_i > \bar{c}_{k^*}$, we have $\psi_i(I, P, \mathbf{x}) = (x_i - \bar{c}_{k^*}) - \frac{x_i - \bar{c}_{k^*}}{\sum_{i' \in \{i \in I : x_i > \bar{c}_{k^*}\}} x_{i'} - \bar{c}_{k^*}} \times \sum_{i' \in \{i \in I : x_i \leq \bar{c}_{k^*}\}} \bar{c}_{k^*} - x_{i'}$. It is direct that $\psi_i(I, P, \mathbf{x}) = \psi_j(I, P, \mathbf{x})$ since $x_i = x_j$.

- ψ satisfies Full distribution (FD).

If $S = 0$, we know that $\psi_i(I, P, \mathbf{x}) = \psi_j(I, P, \mathbf{x}) = 0$. If $S > 0$, by construction, only individuals who have contributed an amount greater than the average cost of the project receive a refund. Let $\hat{I} \equiv \{i \in I : x_i > \bar{c}_{k^*}\}$ be the set of individuals that contribute more than $\bar{c}_{k^*}$. We have to show that $\sum_{i \in \hat{I}} \psi_i(I, P, \mathbf{x}) = \psi_j(I, P, \mathbf{x}) = S$.

$$\begin{aligned}
\sum_{i \in \hat{I}} \psi_i(I, P, \mathbf{x}) &= \sum_{i \in \hat{I}} \left((x_i - \bar{c}_{k^*}) - \frac{x_i - \bar{c}_{k^*}}{\sum_{i \in \hat{I}} x_{i'} - \bar{c}_{k^*}} \times \sum_{i \in I \setminus \hat{I}} (\bar{c}_{k^*} - x_{i'}) \right), \\
&= \sum_{i \in \hat{I}} (x_i - \bar{c}_{k^*}) - \sum_{i \in I \setminus \hat{I}} (\bar{c}_{k^*} - x_{i'}), \\
&= \sum_{i \in \hat{I}} x_i + \sum_{i \in I \setminus \hat{I}} x_{i'} - (\bar{c}_{k^*} \times |I|), \\
&= \sum_{i \in I} x_i - c_{k^*}.
\end{aligned}$$

Since $S = \sum_{i \in I} x_i - c_{k^*}$, we know that ψ satisfies Full distribution (FD).

- ψ satisfies the Monotonicy of Net Payment (MNP).

Suppose $i, j \in I$, without loss of generality, assume that $x_i \geq x_j$. We have to show that $x_i - \psi_i(I, P, \mathbf{x}) \geq x_j - \psi_j(I, P, \mathbf{x})$.

- **Case 1:** If $S = 0$. Then for each $i' \in I$, $\psi_{i'}(I, P, \mathbf{x}) = 0$. Since $x_i \geq x_j$ we have that $x_i - \psi_i(I, P, \mathbf{x}) \geq x_j - \psi_j(I, P, \mathbf{x})$.

- **Case 2:** If $S > 0$, $\bar{c}_{k^*} \geq x_i \geq x_j$. Then $\psi_i(I, P, \mathbf{x}) = \psi_j(I, P, \mathbf{x}) = 0$. Since $x_i \geq x_j$ we have that $x_i - \psi_i(I, P, \mathbf{x}) \geq x_j - \psi_j(I, P, \mathbf{x})$.

- **Case 3:** If $S > 0$, $x_i \geq \overline{c}_{k^*} \geq x_j$. Then $\psi_j(I, P, \mathbf{x}) = 0$. We have to show that $x_i - \psi_i(I, P, \mathbf{x}) \geq \overline{c}_{k^*}$. It follows that

  $$(x_i - \overline{c}_{k^*}) \geq (x_i - \overline{c}_{k^*}) - \frac{x_i - \overline{c}_{k^*}}{\sum_{i' \in \{i \in I: x_i > \overline{c}_{k^*}\}} x_{i'} - \overline{c}_{k^*}} \times \sum_{i' \in \{i \in I: x_i \leq \overline{c}_{k^*}\}} (\overline{c}_{k^*} - x_{i'}). \quad \text{(C.1)}$$

  Since $x_i - \psi_i(I, P, \mathbf{x}) \geq x_i - (x_i - \overline{c}_{k^*})$ by equation (C.1), it is direct that $x_i - (x_i - \overline{c}_{k^*}) \geq \overline{c}_{k^*}$, and therefore $x_i - \psi_i(I, P, \mathbf{x}) \geq x_j - \psi_j(I, P, \mathbf{x})$.

- **Case 4:** If $S > 0$, $x_i \geq x_j \geq \overline{c}_{k^*}$. We have to show that:

  $$x_i \geq x_j - \psi_j(I, P, \mathbf{x}) + \psi_i(I, P, \mathbf{x}).$$

  $$\begin{aligned}
  x_j &+ \psi_i(I, P, \mathbf{x}) - \psi_j(I, P, \mathbf{x}) \\
  &= x_j + (x_i - \overline{c}_{k^*}) - \frac{x_i - \overline{c}_{k^*}}{\sum\limits_{i' \in \{i \in I: x_i > \overline{c}_{k^*}\}} x_{i'} - \overline{c}_{k^*}} \times \sum_{i' \in \{i \in I: x_i \leq \overline{c}_{k^*}\}} (\overline{c}_{k^*} - x_{i'}) \\
  &\quad - \left((x_i - \overline{c}_{k^*}) - \frac{x_i - \overline{c}_{k^*}}{\sum\limits_{i' \in \{i \in I: x_i > \overline{c}_{k^*}\}} x_{i'} - \overline{c}_{k^*}} \times \sum_{i' \in \{i \in I: x_i \leq \overline{c}_{k^*}\}} (\overline{c}_{k^*} - x_{i'}) \right) \\
  &= x_j + x_i - \overline{c}_{k^*} - x_j + \overline{c}_{k^*} \\
  &\quad - \left(\frac{x_i - \overline{c}_{k^*} - x_j + \overline{c}_{k^*}}{\sum\limits_{i' \in \{i \in I: x_i > \overline{c}_{k^*}\}} x_{i'} - \overline{c}_{k^*}} \right) \times \sum_{i' \in \{i \in I: x_i \leq \overline{c}_{k^*}\}} (\overline{c}_{k^*} - x_{i'}) \\
  &\quad x_i - \left(\frac{x_i - x_j}{\sum\limits_{i' \in \{i \in I: x_i > \overline{c}_{k^*}\}} x_{i'} - \overline{c}_{k^*}} \right) \times \sum_{i' \in \{i \in I: x_i \leq \overline{c}_{k^*}\}} (\overline{c}_{k^*} - x_{i'}) \\
  &= x_i - \left(\frac{x_i - x_j}{\sum\limits_{i' \in \{i \in I: x_i > \overline{c}_{k^*}\}} x_{i'} - \overline{c}_{k^*}} \right) \times \sum_{i' \in \{i \in I: x_i \leq \overline{c}_{k^*}\}} (\overline{c}_{k^*} - x_{i'})
  \end{aligned}$$

  Since $x_i \geq x_j$ we know that $\frac{x_i - x_j}{\sum_{i' \in \{i \in I: x_i > \overline{c}_{k^*}\}} x_{i'} - \overline{c}_{k^*}} \geq 0$. Similarly, $\sum_{i' \in \{i \in I: x_i \leq \overline{c}_{k^*}\}} (\overline{c}_{k^*} - x_{i'}) \geq 0$. We therefore have

  $$x_i \geq x_i - \left(\frac{x_i - x_j}{\sum_{i' \in \{i \in I: x_i > \overline{c}_{k^*}\}} x_{i'} - \overline{c}_{k^*}} \right) \times \sum_{i' \in \{i \in I: x_i \leq \overline{c}_{k^*}\}} (\overline{c}_{k^*} - x_{i'}).$$

  This implies that $x_i \geq x_j - \psi_j(I, P, \mathbf{x}) + \psi_i(I, P, \mathbf{x})$.

- ψ satisfies Weak-Consistency (Weak-C).

By definition of (Weak-C), we only need to consider the partitions in which P_k is funded and $k = k^*$. Suppose by contradiction that there exists $i \in I$ such that, without loss of generality $i \in I'$, and $\psi_i(I', P, \mathbf{x}') > 0$ and $\psi_i(I, P, \mathbf{x}) = 0$. We know that the project alternative P_{k^*} is funded in $(I', P, \mathbf{x}')$. Let $\overline{c}'_{k^*} \equiv \frac{c_{k^*}}{|I'|}$. It follows that $\overline{c}'_{k^*} \geq \overline{c}_{k^*}$. If $x_i \leq \overline{c}'_{k^*}$, we know that $\psi_i(I', P, \mathbf{x}') = 0$ which contradict $\psi_i(I', P, \mathbf{x}') > 0$. Suppose $x_i > \overline{c}'_{k^*}$. Since P_{k^*} is funded, and $\psi_i(I', P, \mathbf{x}') > 0$, we know that $S' > 0$.

Claim 1. If $S > 0$ and $x_i > \overline{c}_{k^*}$, then $\psi_i(I, P, \mathbf{x}) > 0$.

Proof. By definition,

$$\begin{aligned}\psi_i(I, P, \mathbf{x}) &= (x_i - \overline{c}_{k^*}) - \frac{x_i - \overline{c}_{k^*}}{\hat{X}} \times \check{X}, \\ &= (x_i - \overline{c}_{k^*}) \times \left(1 - \frac{\check{X}}{\hat{X}}\right).\end{aligned}$$

Since $S > 0$ we know that $\hat{X} > \check{X}$ implying that $\frac{\check{X}}{\hat{X}} < 1$. Therefore, $\left(1 - \frac{\check{X}}{\hat{X}}\right) > 0$. As $x_i > c_{k^*}$, it follows that $\psi_i(I, P, \mathbf{x}) > 0$. ■

We know that $S \geq S'$, therefore, $S > 0$. Since $x_i > \overline{c}'_{k^*} \geq \overline{c}_{k^*}$, by Claim 1 we have that $\psi_i(I, P, \mathbf{x}) > 0$.

- ψ satisfies Weak-Contribution Monotonicity (Weak-CM).

Let $i \in I$ such that $x'_i > x_i \geq c_{k^*}$, and $P_{k'}$ be the funded project alternative in problem $(I, P, (\mathbf{x}_{-i}, x'_i))$. We have to show that

$$\psi_i(I, P, (\mathbf{x}_{-i}, x'_i)) - \psi_i(I, P, \mathbf{x}) \geq (x'_i - x_i) \times \left(1 - \frac{\check{X} \times \hat{X}_{-i}}{\left(\hat{X}_{-i} + x'_i - \overline{c}_{k^*}\right) \times \left(\hat{X}_{-i} + x_i - \overline{c}_{k^*}\right)}\right),$$

if $P_{k^*} = P_{k'}$.
By construction of ψ we know that:

$$\begin{aligned}&\psi_i(I, P, (\mathbf{x}_{-i}, x'_i)) - \psi_i(I, P, \mathbf{x}) \\ &= (x'_i - \overline{c}_{k^*}) - \frac{x'_i - \overline{c}_{k^*}}{\hat{X}_{-i} + x'_i - \overline{c}_{k^*}} \times \check{X} - \left((x_i - \overline{c}_{k^*}) - \frac{x_i - \overline{c}_{k^*}}{\hat{X}_{-i} + x_i - \overline{c}_{k^*}} \times \check{X}\right) \\ &= x'_i - x_i - \check{X} \times \left(\frac{x'_i - \overline{c}_{k^*}}{\hat{X}_{-i} + x'_i - \overline{c}_{k^*}} - \frac{x_i - \overline{c}_{k^*}}{\hat{X}_{-i} + x_i - \overline{c}_{k^*}}\right) \\ &= x'_i - x_i - \check{X} \times \left(\frac{(x'_i - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*}) - (x_i - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x'_i - \overline{c}_{k^*})}{(\hat{X}_{-i} + x'_i - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*})}\right) \\ &= x'_i - x_i - \check{X} \times \\ &\qquad \left(\frac{(x'_i - x_i) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*}) + (x_i - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*})}{(\hat{X}_{-i} + x'_i - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*})}\right.\end{aligned}$$

$$
\begin{aligned}
&\qquad\qquad + \frac{-(x_i - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*}) - (x_i' - x_i) \times (x_i - \overline{c}_{k^*})}{(\hat{X}_{-i} + x_i' - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*})}\Bigg) \\
&= x_i' - x_i - \check{X} \times \left(\frac{(x_i' - x_i) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*} - (x_i - \overline{c}_{k^*}))}{(\hat{X}_{-i} + x_i' - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*})} \right) \\
&= (x_i' - x_i) \times \left(1 - \frac{\check{X} \times \hat{X}_{-i}}{(\hat{X}_{-i} + x_i' - \overline{c}_{k^*}) \times (\hat{X}_{-i} + x_i - \overline{c}_{k^*})} \right)
\end{aligned}
$$

Which concludes the proof.

■

CHAPTER | 5

Chapter 5

Conclusion

In this thesis, we study three models of public goods provision, each addressing distinct economic contexts through complementary methodological approaches.

Chapter 2 introduces a behavioral economic model to explain experimentally observed deviations in public goods provision. We derive conditions for stable coalition formation based on these observations. Unlike standard rational choice theory, our behavioral model incorporates the idea that players do not act a priori as single agents in the decision-making process (Capraro, 2013a). Incentives from rational choice theory remain integral but are embedded within a risk-incentive trade-off. Hence, the model goes beyond pure utility maximization, allowing forecast reasoning where agents mentally simulate how coalitions might form if they act collectively and then behave according to their most optimistic forecasts. This approach complements traditional game theory, which is fundamentally normative, prescribing what rational players should choose (Von Neumann, 1959; Von Neumann and Morgenstern, 2007; Luce and Raiffa, 1957). In contrast, behavioral game theory seeks to explain real-world decision-making (Colman, 2003). We empirically validate and simulate our theoretical contribution using the case of the provision of supranational public goods, through the application of the European Sky Shield Initiative (ESSI). By introducing a novel threat factor, we examine how perceived threats influence individual payoff functions and coalition stability. The results align with recent political developments of the ESSI, predicting both stable and unstable coalitions under various scenarios.

Our key contribution is characterizing conditions for stable coalition structures, which we extend by integrating insights from behavioral economics—originally validated at the individual level—to predict strategic behavior at the level of sovereign countries. We propose a novel method for computing Average Benefit Shares (ABS), specifically applied to supranational goods such as the ESSI. For the provision of supranational public goods, we incorporate heterogeneous ABSs and an exogenous threat factor to determine countries' incentives to contribute. We argue that this approach delivers a more nuanced understanding of the provision of supranational public goods. This framework identifies stable coalition structures characterized by partial, rather than full, cooperation in the provision of supranational public goods, such as the ESSI. The model explains why certain coalitions fail and identifies the conditions under which stable cooperation can emerge. These findings offer concrete insights for the institutional design of collective action without centralized enforcement.

In Chapter 3, we empirically examine European NATO and NATO members, contributing to the burden-sharing literature foundational to Chapter 2.[1] It requires both contributions and benefits in order to assess whether a country over- or undercontributes. As benefits are not directly observable, they must be approximated. The burden-sharing literature suggests that countries align their military expenditures with the benefits derived over time (Sandler and Shimizu, 2014). We propose a novel benefit approximation specifically for European NATO, examining various approximation methods.[2] Political developments, particularly the changing US commitment to NATO, further motivate our focus on the European NATO.

Our key contributions are threefold. First, we examine various weighted ABS measure for European NATO that incorporates GDP, population, and novel proximity-based threat exposure, offering a more nuanced approximation of benefits. Second, we introduce two novel proximity-based threat measures capturing spatial vulnerability to Russian aggression, allowing for a dynamic reassessment of threat exposure over time. Third, we update and extend the empirical analysis of European NATO and NATO burden-sharing from 1993 to 2022 using refined panel data. These innovations enable a reassessment of intra-European burden-sharing patterns, with particular relevance for European NATO and recent initiatives such as the ESSI. We argue that ABS 2 provides the closest statistical match to defense burdens within European NATO and may therefore serve as a suitable proxy when evaluating initiatives such as the ESSI, which can be seen as a functional counterpart to European NATO. We construct a composite ABS 4 that integrates the defined proxies—ABS 1, 2, and 3. ABS 4 fails to exhibit statistical concordance with defense burdens, when tested using the Wilcoxon signed-rank test. However, the combination of these three approximation methods yields a more comprehensive estimator. This is because the individual threat factors underlying ABS 1–3—each a core component of the composite—jointly capture the multidimensional nature of threat exposure more effectively than any single proxy alone. While this outcome points to potential free-riding incentives within European NATO, it does not, by itself, constitute evidence of strategic under- or overcontribution by countries. The question of whether the statistical concordance of ABS 4 constitutes a more comprehensive measure remains open for future research. In doing so, we compare NATO and European NATO purely as different subsets of the same alliance—not to evaluate how Europe might compensate for the absence of US and Canadian contributions.

---

[1] In Chapter 2, we established the conditions for stable coalitions; this estimating the benefit of each country from the European Sky Shield Initiative. The groundwork for Chapter 2 was done in Chapter 3.

[2] This Chapter naturally follows from Chapter 2, where ABS was necessary to establish coalition stability in ESSI.

In Chapter 4, we investigate redistribution rules addressing overcontribution to public goods provision. We examine rules that strike a balance between fairness, participation incentives, and contribution incentives to ensure that contributors are treated equitably. We identify fundamental limitations in the design of rebate rules by demonstrating the impossibility of simultaneously satisfying participation incentives, contribution incentives, and a fairness criterion. To address these constraints, we propose the Proportional Rebate with Threshold (PRT) rule. Beyond satisfying a weaker version of these axioms—Weak-Consistency (Weak-C) and Weak-Contribution Monotonicity (Weak-CM)—this rule also satisfies Equal Treatment of Equals (ETE), Full Surplus Redistribution (FSR), and Monotonicity of Net Payment (MNP).
Our key contribution is the introduction of the Marginal Rebate Contribution, which captures the increase in rebate when an individual's contribution increases. We demonstrate that the PRT rule sustains a higher level of redistribution in cases of overcontribution compared to rebate rules typically used, such as the Shapley rule and the Proportional Rebate rule. More precisely, under these latter rules, when individuals increase their contributions, a significant portion of their additional payment is redistributed to other contributors. We argue that the PRT rule mitigates this effect, making it a more effective rule for balancing incentives and fairness. We show that the PRT rule generates higher redistributions when an individual increases contributions. We argue this strengthens the incentive to contribute.

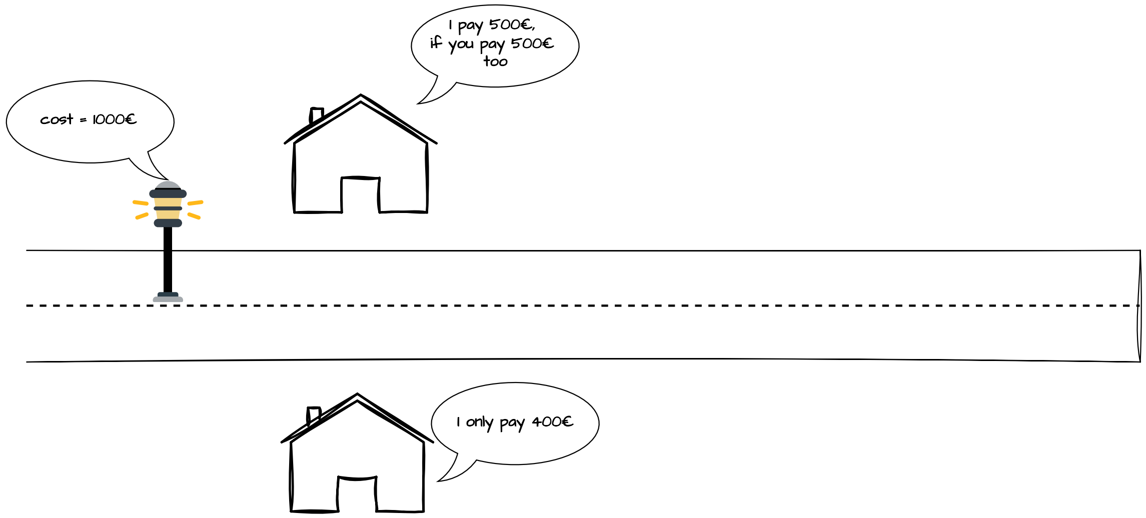
In conclusion, this dissertation contributes by establishing conditions for stable coalitions, developing a fair and robust burden-sharing method for the ESSI and European NATO, and introducing a redistribution method for the provision of public goods that balances desirable axioms, thereby strengthening incentives to contribute to public goods.

Future research avenues include extending Chapter 2 to broader European security contexts, such as customs enforcement and border control, and potentially extending the model to become an explanatory and predictive model for coalitions outside Europe. The conditions for stable coalition structures could also be examined in the context of (non-supranational) public goods. Chapter 3 invites future research work on hybrid threat factors and a dynamic model of European NATO security, replacing the fixed 2% military spending target with a more flexible, well-founded benchmark. The experimental validation of Chapter 4, particularly under conditions where information about provision costs is withheld, could lead to contributions that better reflect the true valuations of individuals and might even be a solution for the provision of public goods for the challenges of cities with budget constraints or deficits.

A Tale of Neighbors, Cooperation and a Streetlight

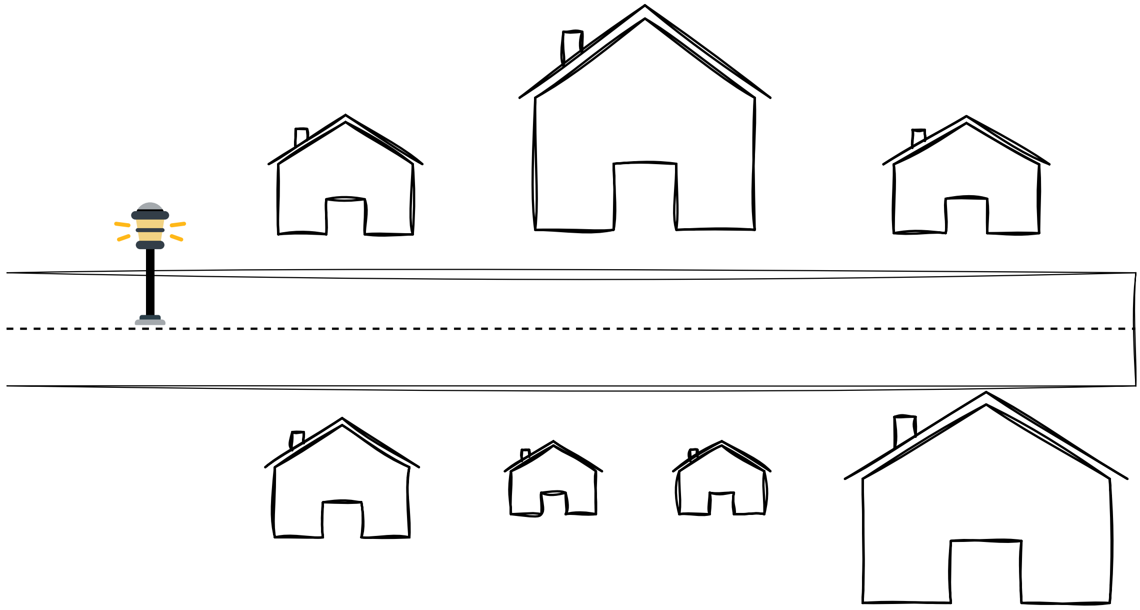
This section offers a intuitive reflection on the central themes of this dissertation. It is inspired by the idea that the essence of complex problems can often be captured through simple stories—accessible to a broader audience.

Imagine two houses facing each other on a dark street. When the residents return home at night, they feel uneasy because there's no streetlight. The two neighbors talk and quickly agree that installing a light would benefit both—it would make the street safer. However, disagreement arises over who should pay. One lives closer to the lamp and expects the other to contribute more; the other insists on splitting the cost 50/50. One is willing to pay €400, the other €500 — but only if the first matches the amount. They fail to agree, and the lamp isn't installed. The public good remains underprovided.



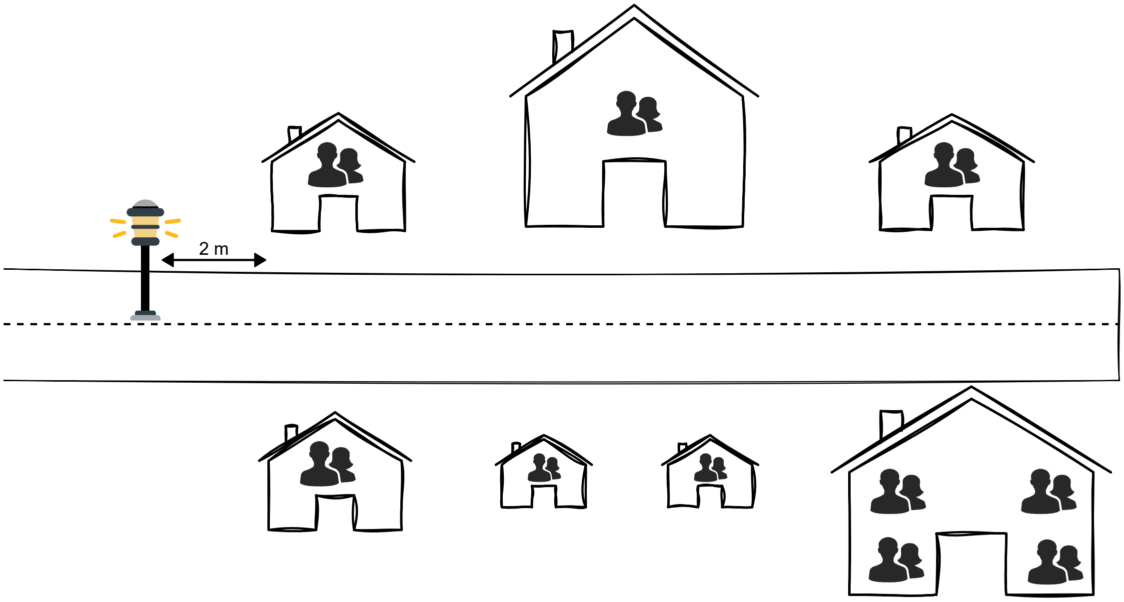
Two neighbors fail to agree on cost-sharing for a streetlight.

Let's assume there is no state to solve the problem. Next, we extend the example: there are large and small houses. Some benefit more from the light—because they are closer to the lamp—others less. What's especially important is that the entrance of the street must be illuminated, as walking there in the dark would be unsafe.



Which houses voluntarily contribute to the financing of the light?

In my first research paper, I ask: Which houses voluntarily contribute to the financing of the light and under what conditions? I focus on situations where some do not contribute—while others still do. But even those contributors may eventually ask themselves: "Why should I pay alone if others don't?"
I also take two key factors into account: first, the season—it's darker for longer in winter—and second, how much light each house actually receives. The light that reaches each house depends not only on its own contribution but also on the house's location (how much light it gets) and the contributions of others. From this, I develop my model.



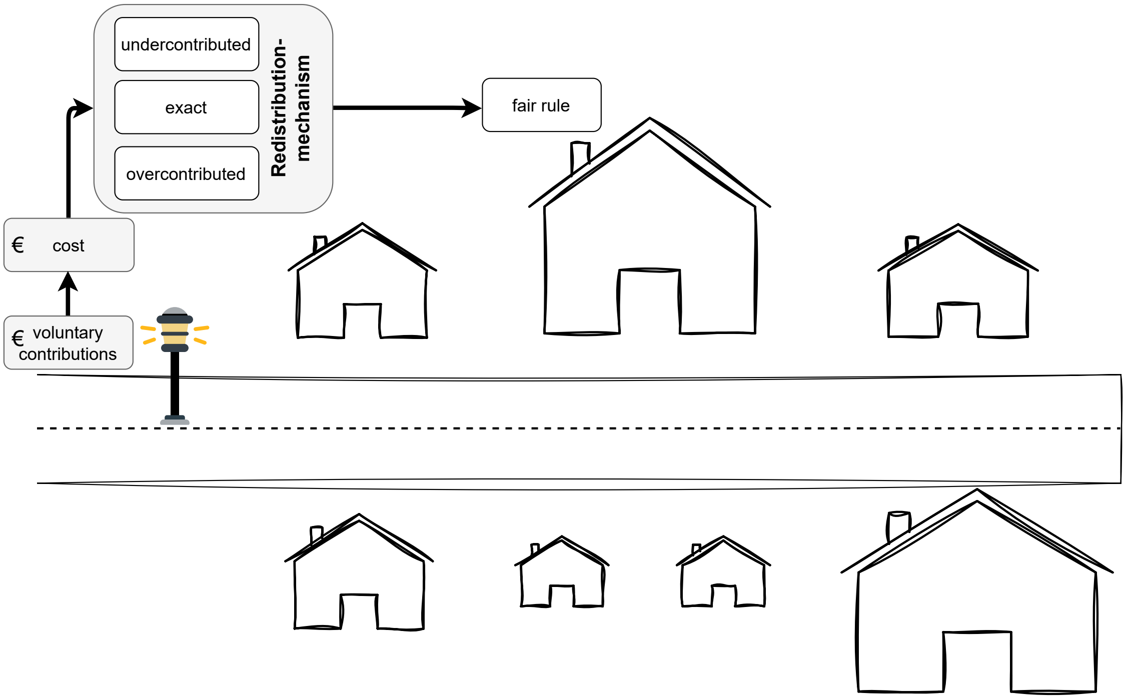
Some houses benefit more than others—depending on location.

In the second research paper, I develop a method to determine how much each house benefits from the light. I consider factors such as the size of the house, the number of its residents, and the distance from the light source. As you can imagine, the results from this paper are used in the first one to account for how much light each house actually receives.

In the third research paper, I focus on the case where voluntary contributions lead to excess funding. Now you might be wondering — didn't I say in the introduction that public goods are typically underfunded due to voluntary contributions? Correct. But here, I focus on what happens when too much is contributed, and how that surplus is redistributed.

That matters, because how the collected funds are redistributed influences willingness to contribute—especially when the cost of providing the light is unknown and contributors are refunded in the case of underfunding.

I develop a rule that determines how the money is redistributed or refunded. I also analyze what properties a "good" rebate rule should have. Simply put: someone who contributes more should receive more back than someone who contributes less.



When the project is overfunded, how should the surplus be redistributed?

This story is simple, but it reflects the heart of the problem. Public goods—whether streetlights or supranational defense—require institutions that make cooperation possible. They require mechanisms that reflect who benefits, who contributes, and how surplus or shortfall is shared. This dissertation explores these issues through formal theory and empirical analysis. But beneath it all, it remains a story of neighbors, cooperation, and the question: Who will pay for the electricity?

Bibliography

Ahlbrecht, M. and Weber, M. (1995). Hyperbolic Discounting Models in Prescriptive Theory of Intertemporal Choice. *Zeitschrift für Wirtschafts- und Sozialwissenschaften : ZWS ; Vierteljahresschrift der Gesellschaft für Wirtschafts- und Sozialwissenschaften - Verein für Socialpolitik*, 115(4).

Ainslie, George (1992). Hyperbolic discounting. In *Choice over time*, 5, pages 57–92.

Akerlof, G. A. (1970). The Market for "Lemons": Quality Uncertainty and the Market Mechanism. *The Quarterly Journal of Economics*, 84(3):488–500. Publisher: Oxford University Press.

Allais, M. (1953). Le Comportement de l'Homme Rationnel devant le Risque: Critique des Postulats et Axiomes de l'Ecole Americaine. *Econometrica*, 21(4):503. Publisher: JSTOR.

Arce M., D. G. and Sandler, T. (2002). *Regional public goods: typologies, provision, financing, and development assistance.* Almquist & Wiksell Internat, Stockholm.

Arnold, S. and Arnold, T. (2023). Deutschlands schwache Führungsrolle bei der europäischen Luftverteidigung: Korrekturbedarf auf allen Ebenen der European Sky Shield Initiative. *SWP-Aktuell*. Publisher: Stiftung Wissenschaft und Politik (SWP), German Institute for International and Security Affairs Version Number: 1.

Axelrod, R. and Hamilton, W. D. (1981). The Evolution of Cooperation. *Science*, 211(4489):1390–1396. Publisher: American Association for the Advancement of Science.

Bagnoli, M. and Lipman, B. L. (1989). Provision of Public Goods: Fully Implementing the Core through Private Contributions. *The Review of Economic Studies*, 56(4):583.

Bagnoli, M. and Mckee, M. (1991). Voluntary Contribution Games: Efficient Private Provision of Public Goods. *Economic Inquiry*, 29(2):351–366.

Barrett, S. (2007). *Why cooperate? the incentive to supply global public goods.* Oxford university press, Oxford.

Becker, J., Kreps, S. E., Poast, P., and Terman, R. (2024). Transatlantic Shakedown: Presidential Shaming and NATO Burden Sharing. *Journal of Conflict Resolution*, 68(2-3):195–229.

Berg, J., Dickhaut, J., and McCabe, K. (1995). Trust, Reciprocity, and Social History. *Games and Economic Behavior*, 10(1):122–142. Publisher: Elsevier BV.

Bergstrom, T., Blume, L., and Varian, H. (1986). On the private provision of public goods. *Journal of Public Economics*, 29(1):25–49.

Bogers, M., Beeres, R., and Bollen, M. (2022). NATO Burden Sharing Research along Three Paradigms. *Defence and Peace Economics*, 33(5):534–547.

Bolton, G. E. and Ockenfels, A. (2000). ERC: A Theory of Equity, Reciprocity, and Competition. *The American Economic Review*, 90(1):166–193. Publisher: American Economic Association.

Buchholz, W. and Sandler, T. (2021). Global Public Goods: A Survey. *Journal of Economic Literature*, 59(2):488–545.

Bundesministerium der Verteidigung (2024). Österreich und die Schweiz beteiligen sich an European Sky Shield Initiative. (Accessed February 2, 2024) https://www.bmvg.de/de/aktuelles/dach-treffen-oesterreich-und-schweiz-beteiligen-sich-an-essi-5651086.

Bundesministerium der Verteidigung (2025). Pistorius: „Frieden kann man nur aus einer Position der Stärke heraus sichern“. (Accessed February 15, 20205); https://www.bmvg.de/de/aktuelles/nato-verteidigungsminister-treffen-bruessel-5889740.

Béal, S., Deschamps, M., Refait-Alexandre, C., and Sekli, G. (2025). Early contributors and fair rewards in crowdfunding. *Theory and Decision. An International Journal for Multidisciplinary Advances in Decision Science*, 98(1):33–59.

Capraro, V. (2013a). A Model of Human Cooperation in Social Dilemmas. *PLoS ONE*, 8(8):e72427.

Capraro, V. (2013b). A solution concept for games with altruism and cooperation. (Accessed June 21, 2023); http://arxiv.org/abs/1302.3988.

Capraro, V., Jagfeld, G., Klein, R., Mul, M., and de Pol, I. v. (2019). Increasing altruistic and cooperative behaviour with simple moral nudges. *Scientific Reports*, 9(1):11880. Number: 1 Publisher: Nature Publishing Group.

Cason, T. N. and Zubrickas, R. (2019). Donation-based crowdfunding with refund bonuses. *European Economic Review*, 119:452–471.

Charness, G. and Rabin, M. (2002). Understanding Social Preferences with Simple Tests. *The Quarterly Journal of Economics*, 117(3):817–869. Publisher: Oxford University Press.

Chemla, G. and Tinn, K. (2020). Learning Through Crowdfunding. *Management Science*, 66(5):1783–1801.

Coats, J. C., Gronberg, T. J., and Grosskopf, B. (2009). Simultaneous versus sequential public good provision and the role of refunds — An experimental study. *Journal of Public Economics*, 93(1-2):326–335.

Colman, A. M. (2003). Cooperation, psychological game theory, and limitations of rationality in social interaction. *Behavioral and Brain Sciences*, 26(2):139–153. Publisher: Cambridge University Press (CUP).

Cooper, R., DeJong, D. V., Forsythe, R., and Ross, T. W. (1996). Cooperation without Reputation: Experimental Evidence from Prisoner's Dilemma Games. *Games and Economic Behavior*, 12(2):187–218.

Cooper, S. and Stiles, K. W. (2021). Who commits the most to NATO? It depends on how we measure commitment. *Journal of Peace Research*, 58(6):1194–1206.

Cumming, D. J., Leboeuf, G., and Schwienbacher, A. (2020). Crowdfunding models: Keep-It-All vs. All-Or-Nothing. *Financial Management*, 49(2):331–360.

Dawes, R. M. (1980). Social dilemmas. *Annual review of psychology*, 31(1):169–193. Publisher: Annual Reviews 4139 El Camino Way, PO Box 10139, Palo Alto, CA 94303-0139, USA.

Deutsche Bundesregierung (2022). 100 Milliarden Euro für eine leistungsstarke Bundeswehr. (Accessed October 14, 2022); https://www.bundesregierung.de/breg-de/themen/sicherheit-und-verteidigung/sondervermoegen-bundeswehr-2047518.

Dreber, A., Ellingsen, T., Johannesson, M., and Rand, D. G. (2013). Do people care about social context? Framing effects in dictator games. *Experimental Economics*, 16(3):349–371.

Dreyer, P., Schnaubelt, C. M., Han, E., Grisé, M., Kepe, M., and Dobbins, J. (2024). Burdensharing and its discontents: Understanding contributions to collective defense in NATO. Technical Report RR-A189-1, RAND Corporation, Santa Monica, CA.

Dunne, J. P. and Tian, N. (2013). Military expenditure and economic growth: A survey. *The Economics of Peace and Security Journal*, 8(1).

Ellsberg, D. (1961). Risk, Ambiguity, and the Savage Axioms. *The Quarterly Journal of Economics*, 75(4):643. Publisher: Oxford University Press (OUP).

Ethan Ilzetzki (2025). Guns and Growth: The Economic Consequences of Defense Buildups. *Kiel Report*, 2.

European Commission (2022). EU steps up action to strengthen EU defence capabilities, industrial and technological base: towards an EU framework for Joint defence procurement.

Fehr, E. and Gächter, S. (2000). Cooperation and Punishment in Public Goods Experiments. *The American Economic Review*, 90(4):980–994. Publisher: American Economic Association.

Fehr, E. and Schurtenberger, I. (2018). Normative foundations of human cooperation. *Nature Human Behaviour*, 2(7):458–468. Number: 7 Publisher: Nature Publishing Group.

Feldman, N. and Shipton, M. (2024). Gunboats and butter: The two percent guideline and NATO burden shifting in the maritime domain. *Contemporary Security Policy*, 45(3):365–395.

George, J. and Sandler, T. (2022). NATO defense demand, free riding, and the Russo-Ukrainian war in 2022. *Journal of Industrial and Business Economics*, 49(4):783–806.

Gintis, H. (2005). Behavioral Game Theory and Contemporary Economic Theory. *Analyse & Kritik*, 27(1):48–72. Publisher: Walter de Gruyter GmbH.

Goeree, J. K. and Holt, C. A. (2001). Ten Little Treasures of Game Theory and Ten Intuitive Contradictions. *American Economic Review*, 91(5):1402–1422.

Goeree, J. K., Holt, C. A., and Laury, S. K. (2002). Private costs and public benefits: unraveling the effects of altruism and noisy behavior. *Journal of Public Economics*, 83(2):255–276.

Goodin, R. E., editor (1996). *The Theory of Institutional Design.* Cambridge University Press, 1 edition.

Guth, W., Schmittberger, R., and Schwarze, B. (1982). An experimental analysis of ultimatum bargaining. *Journal of Economic Behavior & Organization*, 3(4):367–388. Publisher: Elsevier.

Hardin, G. (1968). The Tragedy of the Commons. *Science*, 162(3859):1243–1248.

Hayashi, N., Ostrom, E., Walker, J., and Yamagishi, T. (1999). Reciprocity, Trust, and the Sense of Control: a Cross-Societal Study. *Rationality and Society*, 11(1):27–46. Publisher: SAGE Publications.

Hayek, F. A. (1945). The Use of Knowledge in Society. *The American Economic Review*, 35(4):519–530.

Hirshleifer, J. (1983). From weakest-link to best-shot: The voluntary provision of public goods. *Public Choice*, 41(3):371–386.

Horton, J. J., Rand, D. G., and Zeckhauser, R. J. (2011). The online laboratory: conducting experiments in a real labor market. *Experimental Economics*, 14(3):399–425.

Hurwicz, L. (1973). The Design of Mechanisms for Resource Allocation. *The American Economic Review*, 63(2):1–30. Publisher: American Economic Association.

Isaac, R. M., Schmidtz, D., and Walker, J. M. (1989). The assurance problem in a laboratory market. *Public Choice*, 62(3):217–236.

Isaac, R. M. and Walker, J. M. (1988). Group Size Effects in Public Goods Provision: The Voluntary Contributions Mechanism*. *The Quarterly Journal of Economics*, 103(1):179–199.

Isaac, R. M., Walker, J. M., and Thomas, S. H. (1984). Divergent evidence on free riding: An experimental examination of possible explanations. *Public Choice*, 43(2):113–149.

James Andreoni (1995). Cooperation in Public-Goods Experiments: Kindness or Confusion? *The American Economic Review*, 85(4):891–904. Publisher: American Economic Association.

Kagel, J. H. and Roth, A. E., editors (1995). *The Handbook of Experimental Economics*. Princeton University Press, Princeton, N.J.

Kahneman, D. and Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica*, 47(2):263. Publisher: JSTOR.

Kanbur, S. M. R., Sandler, T., and Morrison, K. M. (1999). *The future of development assistance: common pools and international public goods*. Number no. 25 in ODC policy essay. Overseas Development Council, Washington, DC.

Kaul, I., Grunberg, I., and Stern, M. A., editors (1999). *Global Public Goods: International Cooperation in the 21st Century*. Oxford University Press, Oxford.

Khanna, J. and Sandler, T. (1996). Nato burden sharing: 1960–1992. *Defence and Peace Economics*, 7(2):115–133.

Khanna, J. and Sandler, T. (1997). Conscription, peace-keeping, and foreign assistance: NATO burden sharing in the post-cold war era. *Defence and Peace Economics*, 8(1):101–121.

Kim, W. and Sandler, T. (2024). NATO Security Burden Sharing, 1991–2020. *Defence and Peace Economics*, 35(3):265–280.

Kimball, A. L. (2024). Reconceptualising burdens – NATO centres of excellence: club goods, informal institutions, and partner contributions. *Defence Studies*, 24(4):559–600.

Kramer, R. M., McClintock, C. G., and Messick, D. M. (1986). Social values and cooperative response to a simulated resource conservation crisis. *Journal of Personality*, 54(3):576–582.

Krebs, T. and Kaczmarczyk, P. (2025). Wirtschaftliche Auswirkungen von Militärausgaben in Deutschland. (Accessed July 1, 2025); https://www.vwl.uni-mannheim.de/media/Lehrstuehle/vwl/Krebs/wirt._Auswirk._Militaerausgaben.pdf.

Kuhlman, D. M., Camac, C. R., and Cunha, D. A. (1986). Individual differences in social orientation. *Experimental social dilemmas*, 3:151–176.

Laibson, D. (1997). Golden Eggs and Hyperbolic Discounting. *The Quarterly Journal of Economics*, 112(2):443–477. Publisher: Oxford University Press.

Liebrand, W. B., Wilke, H. A., Vogel, R., and Wolters, F. J. (1986). Value Orientation and Conformity: A Study Using Three Types of Social Dilemma Games. *Journal of Conflict Resolution*, 30(1):77–97. Publisher: SAGE Publications Inc.

Liebrand, W. B. G. (1984). The effect of social motives, communication and group size on behaviour in an N-person multi-stage mixed-motive game. *European Journal of Social Psychology*, 14(3):239–264.

Lindahl, E. (1919). *Die Gerechtigkeit der Besteuerung: Eine Analyse der Steuerprinzipien auf Grundlage der Grenznutzentheorie*. Hakan Ohlssons Buchdruckerei.

Liu, P., Swallow, S. K., and Anderson, C. M. (2016). Threshold-Level Public Goods Provision with Multiple Units: Experimental Effects of Disaggregated Groups with Rebates. *Land Economics*, 92(3):515–533.

Luce, R. D. and Raiffa, H. (1957). *Games and decisions: Introduction and critical survey*. Wiley, New York.

Mankiw, N. G. (2020). *Principles of Economics*. Cengage Learning, Boston, MA, 9 edition.

Marks, M. and Croson, R. (1998). Alternative rebate rules in the provision of a threshold public good: An experimental investigation. *Journal of Public Economics*, 67(2):195–220.

McClintock, C. G. and Liebrand, W. B. (1988). Role of interdependence structure, individual value orientation, and another's strategy in social decision making: A transformational analysis. *Journal of Personality and Social Psychology*, 55(3):396–409. Place: US Publisher: American Psychological Association.

McGuire, C. B., Marschak, J., Radner, R., and Arrow, K. J., editors (1972). *Decision and organization: a volume in honor of Jacob Marschak*. Number 12 in Studies in mathematical and managerial economics. North-Holland Publ. Co, Amsterdam.

Mendez, R. P. (1999). Peace as a Global Public Good. In Kaul, I., Grunberg, I., and Stern, M., editors, *Global Public Goods*, pages 382–416. Oxford University PressNew York, 1 edition.

Miglo, A. (2022). Theories of Crowdfunding and Token Issues: A Review. *Journal of Risk and Financial Management*, 15(5):218.

Murdoch, J. C. and Sandler, T. (1982). A Theoretical and Empirical Analysis of NATO. *Journal of Conflict Resolution*, 26(2):237–263.

Musgrave, R. A. (1939). The Voluntary Exchange Theory of Public Economy. *The Quarterly Journal of Economics*, 53(2):213–237.

Nash, J. F. (1950). Equilibrium points in n -person games. *Proceedings of the National Academy of Sciences*, 36(1):48–49.

Neumann, J. V. and Morgenstern, O. (1944). *Theory of Games and Economic Behavior*. Princeton, NJ, USA.

Nobel Prize Outreach (1988). The Prize in Economics 1988 - Press release. (Accessed July 13, 2025); https://www.nobelprize.org/prizes/economic-sciences/1988/press-release.

Nobel Prize Outreach (2002a). Daniel Kahneman – Facts. (Accessed July 13, 2025); https://www.nobelprize.org/prizes/economic-sciences/2002/kahneman/facts.

Nobel Prize Outreach (2002b). Vernon L. Smith – Facts. (Accessed July 13, 2025); https://www.nobelprize.org/prizes/economic-sciences/2002/smith/facts/.

Nobel Prize Outreach (2007). The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2007. (Accessed July 13, 2025); https://www.nobelprize.org/prizes/economic-sciences/2007/summary/.

North, D. C. (1991). Institutions. *Journal of Economic Perspectives*, 5(1):97–112.

North Atlantic Treaty Organization (2022). 14 NATO Allies and Finland agree to boost European air defence capabilities. (Accessed May 2, 2024); https://www.nato.int/cps/en/natohq/news_208103.htm.

North Atlantic Treaty Organization (2025). Welcome to NATO. (Accessed July 7, 2025); https://www.nato.int/nato-welcome/index.html.

Nowak, M. A. (2006). Five Rules for the Evolution of Cooperation. *Science*, 314(5805):1560–1563. Publisher: American Association for the Advancement of Science.

Nowak, M. A. and Sigmund, K. (1998). Evolution of indirect reciprocity by image scoring. *Nature*, 393(6685):573–577. Number: 6685 Publisher: Nature Publishing Group.

Oezcelik, Y., Gerstmeier, F., and Tolksdorf, M. (2025). "Making the Cut"–Introducing Rebate Rules In Reward-Based Crowdfunding.

Olson, M. (1965). The logic of collective action: Public goods and the theory of groups. *MA: Harvard Univ. Press.*

Olson, M. and Zeckhauser, R. (1966). An Economic Theory of Alliances. *The Review of Economics and Statistics*, 48(3):266–279. publisher: The MIT Press.

Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press, 1 edition.

Ray, D. and Vohra, R. (1997). Equilibrium Binding Agreements. *Journal of Economic Theory*, 73(1):30–78.

Reuters (2024). Polish PM and president at odds over European Sky Shield Initiative. *Reuters*. (Accessed October 23, 2024); https://www.reuters.com/world/europe/polish-pm-president-odds-over-european-sky-shield-initiative-2024-04-16/.

Robbins, L. (1932). *An Essay on the Nature and Significance of Economic Science*. Macmillan, London.

Robert, S. (1993). An Axiomatic Foundation for Regret Theory. *Journal of Economic Theory*, 60(1):159–180. Publisher: Elsevier.

Rondeau, D., D. Schulze, W., and Poe, G. L. (1999). Voluntary revelation of the demand for public goods using a provision point mechanism. *Journal of Public Economics*, 72(3):455–470.

Rose, S. K., Clark, J., Poe, G. L., Rondeau, D., and Schulze, W. D. (2002). The private provision of public goods: tests of a provision point mechanism for funding green power programs. *Resource and Energy Economics*, 24(1):131–155.

Roth, A. E., Prasnikar, V., Okuno-Fujiwara, M., and Zamir, S. (1991). Bargaining and Market Behavior in Jerusalem, Ljubljana, Pittsburgh, and Tokyo: An Experimental Study. *The American Economic Review*, 81(5):1068–1095. Publisher: American Economic Association.

Samuelson, P. A. (1954). The Pure Theory of Public Expenditure. *The Review of Economics and Statistics*, 36(4):387–389.

Sandler, T. (1977). Impurity of Defense: An Application to the Economics of Alliances. *Kyklos*, 30(3):443–460.

Sandler, T. (1998). Global and Regional Public Goods: A Prognosis for Collective Action. *Fiscal Studies*, 19(3):221–247. Publisher: Wiley.

Sandler, T. (2004). *Global Collective Action*. Cambridge University Press, Cambridge, England ; New York.

Sandler, T. (2013). Buchanan clubs. *Constitutional Political Economy*, 24(4):265–284.

Sandler, T. and Forbes, J. F. (1980). Burden Sharing, Strategy, and the Design of NATO. *Economic Inquiry*, 18(3):425–444.

Sandler, T. and Murdoch, J. C. (2000). On Sharing NATO Defence Burdens in the 1990s and Beyond. *Fiscal Studies*, 21(3):297–327.

Sandler, T. and Shimizu, H. (2014). NATO Burden Sharing 1999-2010: An Altered Alliance. *Foreign Policy Analysis*, 10(1):43–60.

Shimizu, H. and Sandler, T. (2003). NATO Peacekeeping and Burden Sharing: 1994-2000. *Public Finance Review*, 31(2):123–143.

Smith, V. L. (1980). Experiments with a decentralized mechanism for public good decisions. *The American Economic Review*, 70(4):584–599.

Spencer, M. A., Swallow, S. K., Shogren, J. F., and List, J. A. (2009). Rebate rules in threshold public good provision. *Journal of Public Economics*, 93(5-6):798–806.

Strausz, R. (2017). A Theory of Crowdfunding: A Mechanism Design Approach with Demand Uncertainty and Moral Hazard. *American Economic Review*, 107(6):1430–1476.

US Central Intelligence Agency (2024). The World Factbook. (Accessed November 18, 2024); https://www.cia.gov/the-world-factbook/.

Von Neumann (1959). 1. On the Theory of Games of Strategy. In *Contributions to the Theory of Games (AM-40), Volume IV*, pages 13–42. Princeton University Press.

Von Neumann, J. and Morgenstern, O. (2007). *Theory of Games and Economic Behavior (60th Anniversary Commemorative Edition)*. Princeton University Press.

Warr, P. G. (1983). The private provision of a public good is independent of the distribution of income. *Economics Letters*, 13(2-3):207–211.

World Bank (2024). World Databank. (Accessed November 18, 2024); Military Expenditure: https://data.worldbank.org/indicator/MS.MIL.XPND.GD.ZS (Original source: SIPRI Military Expenditure Database); Population: https://data.worldbank.org/indicator/SP.POP.TOTL (Original sources: UN Population Division (World Population Prospects), Eurostat, and national statistical offices); GDP: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD (Original sources: World Bank, OECD National Accounts, national statistical organizations, central banks, and World Bank staff estimates).

Zubrickas, R. (2014). The provision point mechanism with refund bonuses. *Journal of Public Economics*, 120:231–234.

Declaration

During the preparation of this work the author(s) used the following generative AI and AI-assisted technologies:

- DeepL and Grammarly for language editing;
- ChatGPT for refining sentence structure and clarity.

After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Curriculum Vitae

Resul Zoroğlu

09/2024 – 03/2025	Visiting Scholar Boston College, USA Sponsor: Prof. Utku Ünver
03/2022 – 09/2025	Ph.D. Student Karlsruhe Institute of Technology, Germany Department of Economics Chair of Economic Policy: Prof. Ingrid Ott
10/2018 – 02/2022	M.Sc. Econ. Engineering Karlsruhe Institute of Technology
10/2017 – 08/2018	M.Sc. Economics Heidelberg University, Germany
01/2017 – 03/2017	Semester Abroad Pompeu Fabra University, Spain
10/2016 – 01/2017	Semester Abroad Bogazici University, Turkey
09/2014 – 08/2017	B.Sc. Economics University of Mannheim, Germany
09/2011 – 06/2014	Pädagogium Baden-Baden, Abitur