System of Systems Engineering for Policy Design

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Systems Design Engineering

Waterloo, Ontario, Canada, 2013

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

A system of systems (SoS) framework is proposed for policy design that takes into account the value systems of multiple participants, harnesses the complexity of strategic interactions among participants, and confronts the risks and uncertainties present in participants' decision making. SoS thinking provides an integrative and adaptive mindset, which is needed to tackle policy challenges characterized by conflict, complexity, and uncertainty. With the aim of putting SoS thinking into practice, operational methods and tools are presented herein. Specifically, SoS engineering methodologies to create *value system models*, *agent-based models of competitive and cooperative behaviour under conflict*, and *risk management models* are developed and integrated into the framework. The proposed structure, methods and tools can be utilized to organize policy design discourse. Communication among participants involved in the policy discussion is structured around SoS models, which are used to integrate multiple perspectives of a system and to test the effectiveness of policies in achieving desirable outcomes under varying conditions.

In order to demonstrate the proposed methods and tools that have been developed to enliven policy design discourse, a theoretical common-pool resources dilemma is utilized. The generic application illustrates the methodology of constructing ordinal preferences from values. Also, it is used to validate the agent-based modeling and simulation platform as a tool to investigate strategic interactions among participants and harness the potential to influence and enable participants to achieve desirable outcomes. A real-world common pool resources dilemma in the provisioning and security considerations of the Straits of Malacca and Singapore is examined and employed as a case study for applying strategic conflict models in risk management. Overall, this thesis advances the theory and application of SoS engineering and focuses on understanding value systems, handling complexity in terms of conflict dynamics, and finally, enhancing risk management.

Acknowledgements

This research was sponsored by the Social Sciences and Humanities Research Council (SSHRC) of Canada and the Natural Sciences and Engineering Research Council (NSERC) of Canada, as well as the Centre for International Governance Innovation (CIGI). It was largely completed during the tenure of an SSHRC Canada Graduate Scholarship.

My PhD program was a pleasant experience due to several key institutions: 1) My thanks to fellow members of the *Conflict Analysis Group*, past and present, for kindness and camaraderie; 2) I am indebted to my *in-laws*, Jack and Mill, for room and board; thank you for treating me like a daughter; 3) I would also like to acknowledge the administration and staff of the *Department of Systems Design Engineering*; 4) finally, I benefited immensely from serving on the Executive of the *Graduate Student Association*.

I would like to express my deep appreciation to Professor Norio Okada, former Director of the Disaster Prevention Research Institute at Kyoto University, for giving me the opportunity to participate in the workshops for the International Risk Governance Council project on the "Risk Governance of Maritime Global Critical Infrastructure," which took place in Kyoto Japan in 2009 and 2010.

Valuable feedback on the scientific, engineering and philosophical content of this thesis has been provided by my examination committee. I would like to thank my External Examiner, Prof. R. L. Keeney from Duke University, and other committee members: Prof. T. Homer-Dixon of the School of Enterprise, Environment and Development, Prof. P. Fieguth of the Department of Systems Design Engineering, and Prof. M. De from Wilfrid Laurier University, for taking the time to read this thesis and provide helpful suggestions.

Lastly, I wish to express my sincere gratitude and appreciation for the time and commitment that has been provided by my supervisors, Prof. K. W. Hipel and Prof. L. Fang. They are sources of endless encouragement and systems thinkers *par excellence*. I am grateful to both of them for recognizing my potential and providing me with an abundance of opportunities to develop professionally and personally.

Dedication

To my husband and daughter

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List of Abbreviations

Abbreviation	Full Meaning
ABMS	Agent Based Modeling and Simulation
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CPR	Common Pool Resource(s)
DM	Decision Maker
DSS	Decision Support System
ECON	Economic-focused
ENV	Environmental-focused
ETC	Action Group on Erosion, Technology and Concentration
FAO	United Nations Food and Agriculture Organization
GDP	Gross Domestic Product
GMCR	Graph Model for Conflict Resolution
GMR	General Metarationality / General Metarational
HDI	Human Development Index
HNS	Hazardous and Noxious Substances
HT	Hazards and Threats
IRGC	International Risk Governance Council
IRRI	International Rice Research Institute
LIFDC	Low Income Food Deficit Countries
MCDA	Multiple Criteria Decision Analysis
RM	Risk Management Strategies
SEQ	Sequential stability / Sequentially stable
SMR	Symmetric Metrationality / Symmetic Metarational
SOC	Societal-focused
SoS	System of Systems
TTEG	Tripartite Technical Experts Group (Straits of Malacca and Singapore)
UI	Unilateral Improvement
UM	Unilateral Move
UN	United Nations
US	United States of America
USD	American Dollars
VFT	Value Focused Thinking
WHO	World Health Organization
WTO	World Trade Organization

List of Symbols

Symbol	Meaning
α	Reorganization phase of the adaptive cycle
β	tradeoff of one less over-appropriator for catching an over-appropriator
$\gamma, \delta, \varepsilon$	dummy counters for AHP calculations
ι	a DM that is not DM i
κ	Conservation phase of the adaptive cycle
Ω	Release phase of the adaptive cycle
$\Omega_H(s, s_1)$	set of DMs who could have made the last UM in the sequence UMs from s to s_1
$\Omega_H^+(s, s_1)$	set of DMs who could have made the last UI in the sequence UIs from s to s_1
A	set of arcs in an integrated graph, IG
A_i	set of directed arcs in a GMCR, which contain the movements in one step controlled by DM i
B_i	set of DM i's best responses to countermoves of other DMs
B_{kl}	lth attribute of the kth fundamental objective
C_{kl}	criterion/threshold point of the lth attribute of the kth fundamental objective
D_{kl}	cumulative performance difference of state s compared to all other states in Q on the lth attribute of the kth fundamental objective
E	cost to monitor
E_H	set of terminal UMs by DMs in H
E_i	set of terminal UIs by DM i
E_i^+	set of terminal UIs by DM i for which there are no multilateral improvements by other DMs
F	fine imposed by a monitor for over-appropriating
$F_o(x)$	relative frequency of x agents over-appropriating
G	graph structure of a GMCR
G_i	DM i's directed graph
H	subset of DMs in N (not in a coalition)
IG	integrated graph of all DMs' directed graphs
K	number of fundamental objectives
L	additional benefit obtained through over-appropriation in one time step
L_k	number of attributes to measure the kth fundamental objective
M	total benefits for each DM if everyone took a fair share
N	set of DMs
O_i	set of options controlled by DM i
O	set of all options
$\mathbb{O}_k$	kth fundamental objective

Symbol	Meaning
P	cumulative probability function
$\mathcal{P}_i$	decision rules for DM i
Q	subset of states in S to be compared to state s
R	reward for catching an over-appropriator
R_H	set of multilateral moves by H from an initial state s
R_H^+	set of multilateral improvements by H from an initial state s
R_i	DM i's set of UMs from an initial state s
R_i^+	DM i's set of UIs from an initial state s
$R_{i,GMR}^+$	DM i's set of UIs from an initial state s that are not GMR stable
$R_{i,SMR}^+$	DM i's set of UIs from an initial state s that are not SMR stable
$R_{i,SEQ}^+$	DM i's set of UIs from an initial state s that are not SEQ stable
$\mathcal{R}$	risk
S	set of states (outcomes) in a GMCR
S_{BE}	combined set of best responses and terminal UMs by other DMs
S_{WE}	combined set of worst-case scenarios and terminal UIs
S_{WE}^+	combined set of worst-case scenarios consisting of a sequences of UIs and a multilateral improvements and terminal UIs for which there are no multilateral improvements by other DMs
$\mathbb{S}$	system
U	uniform distribution
V_i	DM i's payoff function
V^{OP}	score obtained using the Optimizer-Prioritization scheme
V^{OW}	score obtained using the Optimizer-Weighting scheme
V^{SP}	score obtained using the Satisficer-Prioritization scheme
V^{SW}	score obtained using the Satisficer-Weighting scheme
W_i	set of worst-case scenarios from the perspective of DM i
W_i^+	set of worst-case scenarios from the perspective of DM i consisting of a sequences of UIs and a multilateral improvements
✖	Does not select a given option
✓	Selects a given option
✖✖	Strategy 1: takes a fair share and does not monitor
✖✓	Strategy 2: takes a fair share and monitors
✓✖	Strategy 3: over-appropriates and does not monitor
✓✓	Strategy 4: over-appropriates and monitors
a_x	binomial coefficient, where x corresponds to the number of appropriators
b_0	individual unit benefit of not contributing while another DM does
b_1	mutual unit benefit of contributors
b_{kl}	specific amount of B_{kl}

Symbol	Meaning
Δb_{kl}	smallest amount of change in the attribute B_{kl}
$[b_{min}, b_{max}]$	range of an attribute’s numeric values
c_0	mutual unit cost of non-contributors
c_1	individual unit cost of contributing while another DM does not
c_{kl}	mapping function of a criterion
d_{kl}	mapping function of state q compared to state s on the lth attribute of the kth fundamental objective
e	a state in E_i or E_i^+
f	mapping function of a state s
f_s	h-dimensional vector denoting state s
g	mapping function of a strategy for DM i
g_i^s	m_i-dimensional vector denoting DM i’s strategy corresponding to state s
$g_{i,j}^s$	indicates whether or not option o_{ij} is selected by DM i
$\bar{g}_{i,j}^s$	Complement of $g_{i,j}^s$
h	number of options in the set O
i	a DM’s unique identifier
iff	if and only if
j	an option’s unique identifier
k	an objective’s unique identifier
k_{degree}	degree of variability
l	an attribute’s unique identifier
m_i	number of options controlled by DM i
n	number of DMs
n_s	number of states in a GMCR model
n_j	number of DMs who selected option $o_{\iota j}$
$n_j^{s,i}$	number of DMs, excluding DM i, who selected option $o_{\iota j}$ in state s
$n_{1\cap 2}$	number of DMs who monitor at the same time that their neighbor in front over-appropriates
$n_{1\cap 2}^{s,i}$	number of DMs, excluding DM i, who monitor at the same time that their neighbor in front, who is also not DM i, over-appropriates in state s
o_{ij}	jth option of DM i
p_z	probability of scenario s_z
q	a state in Q to be compared with state s
r	Exploitation phase of the adaptive cycle
r_{kl}	rank of the lth attribute of the kth fundamental objective
$r_{\mathbb{O}_1:\mathbb{O}_2}$	pairwise comparison between objectives $\mathbb{O}_1$ and $\mathbb{O}_2$
$r_{B_{k1}:B_{k2}}$	pairwise comparison between attributes B_{k1} and B_{k2}
s	state (also referred to as outcome or scenario) in a GMCR model

Symbol	Meaning
s^*	highest ranked (maximally preferred) state
s^{**}	best worst-case scenario
s^{***}	best worst-case of the best response scenario
$s(t)$	state of a conflict at time t
$s_1, s_2, \dots, s_{n_s}$	elements in S
s_z	scenario
t	time
$\tilde{u}$	random variable with a uniform probability distribution
$\boldsymbol{u}(t)$	probability of initiating events and their specificity
v	a given input value
$\tilde{v}$	random variable specifying possible values of a perturbed input
w_k	importance of the kth fundamental objective
w_{kl}	importance of the lth attribute of the kth fundamental objective
$\mathscr{w}_k$	intermediary variable in the calculation of w_k
$\mathscr{w}_{kl}$	intermediary variable in the calculation of w_{kl}
$\boldsymbol{x}(t)$	state vector of a system
x	number of over-appropriators
Δx	change in the number of over-appropriators from t to $t+1$
y_z	Consequence of scenario s_z
$\boldsymbol{y}(t)$	probability and severity of consequences
z	counter for scenarios
$\succcurlyeq_i$	DM i's strict preference and indifference relations on S
$\succ_i$	DM i's preference relations on S
$\sim_i$	DM i's indifference relations on S
$\succ_i^2$	DM i's second-order preference relations on S
$\sim_i^2$	DM i's second-order indifference relations on S
$\in$	is an element of
$\subseteq$	is a subset of
$\subset$	is a proper subset of
$S \times S$	the set of all ordered pairs with the first element of each pair selected from S and the second element also selected from S
$\neq$	not equal
$\emptyset$	null set
$\cup$	union operator
$\forall$	for all

Chapter 1

Introduction

The developments of this thesis are devised to address challenges in a complex and uncertain world. In Section 1.1, the context for this work is presented. In Section 1.2, system of systems design is discussed as an integrative and adaptive approach to tackle problems with high complexity and uncertainty. The objectives of this thesis are introduced in Section 1.3 and the organization of this thesis is outlined in Section 1.4.

1.1 A complex and uncertain world

Humans in a social unit and as a society can do great things. Among social beings, there are relationships that bind one to another which are needed for the survival of individuals who depend on each other. Some of these relationships are natural, such as between parents and their children, and others are negotiated, such as between a buyer and a seller. In order to create a functional relationship, there must be cooperation in the sense that both parties need to agree to the considerations owed to the other. Through cooperation, they achieve a goal that could not be reached by individual efforts alone.

The ability to cooperate to achieve mutually beneficial outcomes, however, does not distinguish us from other creatures. In nature, animals of some species work together and symbiotic relationships among different species are observed (Paracer and Ahmadjian, 2000; Begon et al., 2006). Perhaps it may be argued that humans distinguish their accomplishments from those of nature by freely choosing to cooperate. For example, parents choose to raise a child together. As another example, a free market is one without external interventions so that buyers and sellers can agree on the true value of a commodity and decide whether or not to trade with each other. It is the ability to choose freely that raises cooperative human achievements to an extraordinary level because the paths taken are not completely random, predetermined, or forced by nature.

Indeed, the other consequences of free will are outcomes in which parties consider an agreement but do not enter into a contract, or after making a deal, break the bond and walk away with penalties incurred to some extent by both parties. Humans may take these options because competitive relationships also exist alongside cooperative ones. Many other duties and ambitions compete with our children for time; many sellers interact with one another for increasing their market share. Thus, competition which promotes the creation of comparable alternatives is required for free will to be manifested.

Furthermore, competition is a process that can enhance efficiency in a system, given that certain conditions are met. For example, competition should encourage optimal pricing in a free market given, among other assumptions, perfect information (Debreu, 1959). In some observed situations where necessary conditions are not met, however, competition can contribute to unintended consequences and degrade the system. In the case of a free market, the moral good of private property is presupposed (McMurtry, 2002); but when resources are not owned privately, the "invisible hand" of the free market falters. Sub-optimal outcomes are observed in common-pool resources (CPR), which are distinguished by a high difficulty to exclude users and a high subtractability that diminishes benefits to the group when a new user is added (Ostrom, 1990; Ostrom et al., 1994, 1999). In CPR situations, rules need to be negotiated to prevent degradation of a resource. Over time, these rules become institutions which are founded on social contracts and enforced through interactions such as communication and sanctions. Hence, cooperation is needed to overcome unintended consequences of competition.

As a result of many interactions among autonomous beings, complexity arises. When one person is in charge, as in a dictatorship, the system of control is relatively simple. When two persons have power to make their own decisions and influence others, there is complexity. As more independent components are added to a system, complexity of the system increases. Cooperation and competition are two types of interactions which are of particular interest in conflict situations. In purely competitive relationships, opponents should act in their own self-interests. As a result, they can expect others to behave in the same way and determine how to maximize their own payoffs or achieve the best standings according to which positions are more preferred. In cooperative-competitive relationships, however, the outcome can be further affected by values, attitudes, and beliefs, which can affect preferences more than just payoffs. Preferences of an individual can be modified by a change in one's value system or alternative positions may be sought to satisfy a given set of values (Keeney, 1992). Discourse on the level of values rather than positions is a way to broaden the solution space such that mutually beneficial outcomes that were originally hidden become reachable (Fisher et al., 1981, 1991; Raiffa, 1982; Ury, 1991, 1993). Furthermore, cooperation may be made possible or hindered depending on whether or not there are good relations among opponents in terms of a good attitude towards each other or good faith in each others' promises.

Uncertainty from a variety of sources in a complex world is a challenge and addressing it is a factor in the success of human cooperation and competition. Despite complexity, certainty in the rationality of decision makers (DMs) to maximize payoffs in competitive relationships helps opponents to formulate strategies. Cooperative-competitive interactions, however, have an element of uncertainty. Human behaviour may appear "irrational". It is a challenge first, to know one's own and others' preferences, and second, to predict the outcome as a result of decisions made by all interacting participants. Moreover, the uncertainty in human interactions is further compounded by uncertainty in the consequences of actions that affect the Earth's systems in time and space. Many technological systems are in place to support a desirable quality of life for obtaining more and more resources. Interactions among societal systems, technological systems and environmental systems add to the complexity which can enrich or encumber the Earth and its inhabitants. However, much political debate is about the uncertainty on the impact of business-as-usual on future generations and neighbours near and far (Lomborg, 2001; Stern, 2007). Disagreement inhibits collective action, especially disagreement due to uncertainty in the required actions to avoid a disaster (Barrett and Dannenberg, 2012). Without conflict resolution mechanisms and ways to confront and deal with uncertainty, the likely outcome of strategic interactions in cooperative-competitive situations is a "Tragedy of the Commons." This occurs when the dominant strategy of all participants is to extract as much from the commons as possible to the point that the system collapses, which is a tragedy (Hardin, 1968).

Humans, however, are not bound to a predetermined fate. Where participants in CPR dilemmas agree on and manage institutions to govern human interactions, it is possible to avoid a Tragedy of the Commons (Ostrom, 1990). In particular, conflict resolution mechanisms are needed to harness complexity that enriches the world, which is to say to promote relationships that achieve mutually beneficial outcomes. Moreover, DMs need ways to deal with uncertainty and effectively manage their risks within a system of systems consisting of societal, technological and environmental systems. Although it is not currently possible to control such a system of systems in a classical sense, new thinking and methods are needed to solve problems integratively, adaptively, and ethically as we address continuing and emerging challenges in a complex and uncertain world.

The approach that is adopted in this thesis is a System of Systems (SoS) approach. A SoS approach is motivated by the characteristics listed in Table 1.1. The independence of components in a SoS, which gives rise to complexity, and the general lack of control which is mainly due to unexpected emergent behaviour and unknown evolutionary paths, requires a new way to approach problems. SoS engineering extends and goes beyond systems engineering methods to address systemic problems that involve multiple independent systems that face unique challenges of conflicts, complexity, and uncertainty. The arguments in this thesis present an epistemological standpoint that these challenges can be overcome with more knowledge.

Table 1.1: Summary of differentiating characteristics between a system of sub-systems and a system of systems.

	System of sub-systems (Complicated Systems)	**System of systems (Complex Systems)**
Necessary	Operational Dependence of Components Centralized Control of Components	Operational Independence of Components Managerial Independence of Components
Follows	Localized Distribution (Predictable) Emergent Behaviour End-Product Development	Geographic Distribution (Unexpected) Emergent Behaviour Evolutionary Development

1.2 System of systems design

Challenges in the 21st century require new, refined and expanded systems methods that shift from a systems to a SoS perspective, a disciplinary to a multidisciplinary understanding, and a steady-state to a real-time horizon (Hipel et al., 2007). A SoS consists of interacting components that are systems in and of themselves as distinguished by being managerially or operationally independent (Maier, 1998). As a result, a SoS is also characterized by features of emergent behaviour, evolutionary development, adaptation, and self-organization (Sage and Cuppan, 2001; Sage and Biemer, 2007). In a manner that is transparent, tractable, and scientifically sound, SoS engineering seeks to tackle problems that are deadlocked by overwhelming conflict, complexity, and uncertainty.

The models designed in this thesis can be used to facilitate understanding through analysis and synthesis in the four phases of a generalized SoS design process. Figure 1.1 illustrates a general SoS design process. There are four main phases: 1) pluralistic problem definition, 2) alternatives generation, 3) negotiations and multiple participant decision making, and 4) implementation, including monitoring, evaluation and conflict resolution (Heng, 2009). At the center is the use of SoS models to transform participants' understanding of the SoS. Different levels of envisioning the SoS are represented by quadrants separated by the four phases of the design process.

1) First, participants develop a pluralistic definition of the problems to be addressed by viewing a policy challenge from multiple perspectives through the formation of models. Participants invest hard thinking and reflection on their value systems in relation to the outcomes of their own and others' decisions. Through the creation of models from multiple perspectives in the problem definition phase, participants take in information about the SoS as it is and output what they perceive.
2) For each participant, a *value system model* is generated using value focused thinking, the analytic hierarchy process and a comparison-aggregation scheme to determine a participant's ordinal preferences. Using these preferences in a simulation platform for *agent-based modeling of competitive and cooperative behaviour under conflict*, the likely outcomes of strategic interactions among participants are obtained. The simulated world

of agents becomes a laboratory to test new rules on whether or not they enable participants to generate alternative outcomes that achieve desirable consequences according to their value systems. Consequently, participants partake in an iterative and creative design process through the modeling and simulation exercises to generate alternatives. In this phase, participants create pathways to move the state of the SoS to a state that they desire.

3) Furthermore, the SoS models can provide negotiation and decision making support to participants. DMs in a conflict require a low-cost arena for negotiating agreements, including an arrangement on the mechanism for conflict resolution to promote peaceful interactions. As a tool, stakeholders can use the agent-based modeling and simulation platform to analyze conflict dynamics and to suggest trajectories that would lead to mutually beneficial outcomes. Moreover, participants face many uncertain factors in their decision making. Hence, *a system of systems engineering methodology for risk analysis*, which takes into account strategic interactions among participants, is also developed. As a result of this phase, participants negotiate and make decisions, which can be facilitated by models that show what could be achieved within a given framework based on what is desired.
4) Finally, actions are implemented but require continuous monitoring and evaluation so that participants are provided with a sense of the SoS as it is. Moreover, a conflict resolution mechanism is also needed so that participants with grievances have recourse to a governing body when the agreements entered into lead to unexpected or undesirable outcomes. The actual outcome that results from decisions taken by the participants can be evaluated with value system models. The design process is an iterative loop wherein meaningful attributes need to be measured and constructively fed back into the process to improve and adapt institutions when they are considered ineffective.

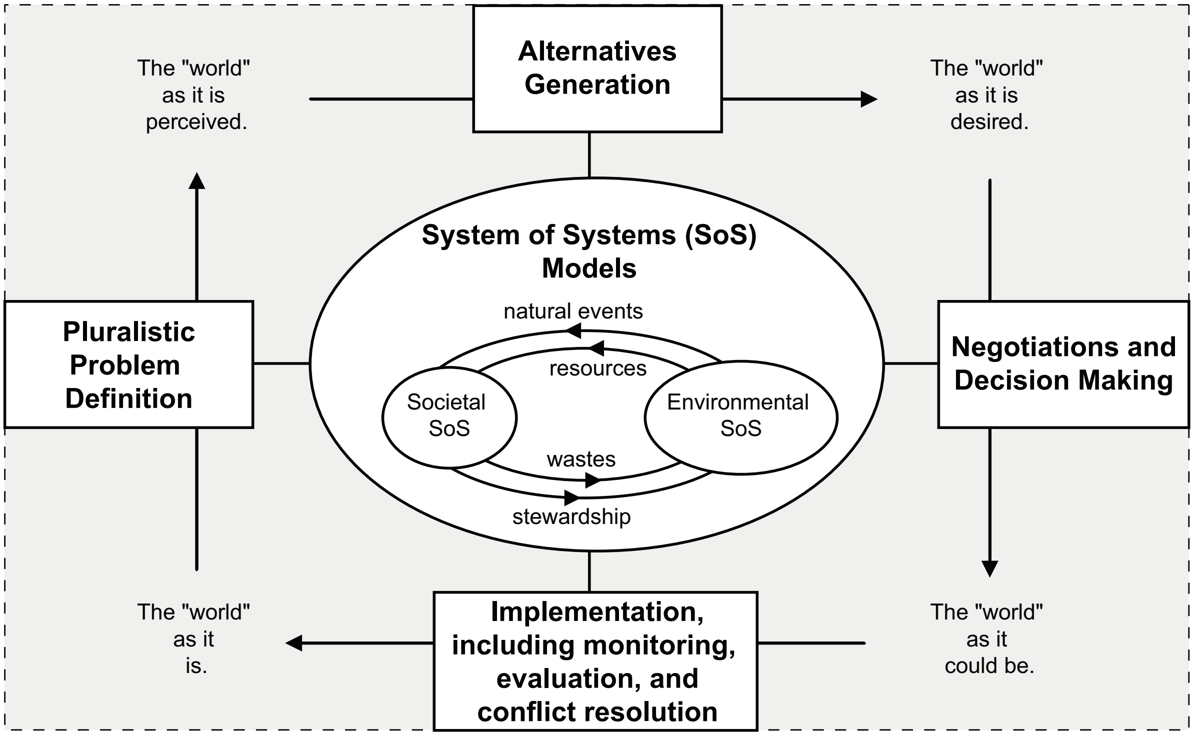


Figure 1.1: System of systems design process.

In this thesis, SoS engineering concepts are utilized to operationalize SoS thinking. SoS engineering extends systems engineering by expanding the problem definition from a single system's perspective to a plurality of perspectives. Since there are many DMs with different and potentially conflicting objectives, participants in the design process should focus on generating alternatives that satisfy the values of DMs. Additionally, efforts may be needed to neutralize negative relations among DMs. The groundwork in understanding how one's own and others' values affect decision making and in cultivating trust among DMs is foundational for effective negotiation (Pruitt, 1981; Raiffa, 1982). In the case where DMs self-identify with a group, decision making methods need to be expanded to group decision making. In any situation, solutions should incorporate conflict resolution requirements in order to address SoS challenges integratively and adaptively. Indeed, multiple interconnected solutions may constitute a solution. Since a SoS is dynamic and contexts also change, implementation also needs to be able to adapt. Hence, monitoring and evaluation should be continuous and fed back into the SoS so that appropriate solutions are applied. In the next round of a SoS engineering design cycle, some solutions may disappear, some may be refined and new ones may be generated.

1.3 Research objectives

In this thesis, a SoS engineering framework is proposed to harness complexity and deal with uncertainty. The overall objective is to create a framework along with methodologies and tools to support participants engaged in a SoS engineering design process. Development of the SoS engineering framework is focused on capturing how values, strategic interactions, and risk perceptions affect outcomes of societal interactions in a SoS. Within this framework, three methodologies are developed to achieve three interrelated objectives. The first objective is to relate values of DMs to outcomes. The second goal is to expand decision making rules in agent-based modeling and simulation to consider strategic interactions. The third objective is to integrate risk analysis with strategic analysis in order to relate how risk perception and strategic interactions affect risk management outcomes. The product of this research work culminates in a simulation platform for testing solutions to SoS challenges. Simulations are less expensive than physical experiments. As a design tool, simulations can be used to test hypotheses on which conditions lead to desired outcomes, and thus how a SoS may be designed so that participants can achieve SoS-level goals.

More specifically, new methodologies are needed in order to operationalize SoS thinking for policy development. First, to better understand value systems of participants in a conflict, a way to relate decisions in a conflict situation to preferences and preferences to a value system is required. Preferences need to be constructed dynamically and in the context of a conflict. Second, to be able to create rules that make use of complexity or the relationships that exist among participants, a systematic method to model and simulate multiple-participant conflict dynamics would be useful to study the effect of rules on outcomes. The models serves as a communication tool to synthesize a SoS perspective and the simulations enable what-if scenario analysis. Third, to improve risk management in a SoS, strategic considerations should be integrated with risk analysis. Risk management employs strategy when preferences match risk perception and tolerances and the moves of other participants are factored into the decision on which risk management options to take. The purpose of this thesis is to develop new methodologies and demonstrate their usefulness with test-run models.

1.4 Organization of this thesis

Figure 1.2 outlines the organization of this thesis. In Chapter 2, a review of SoS thinking is presented and organized into three main aspects: 1) values, 2) complexity, and 3) risk. A policy development framework is developed based on these three pillars of SoS thinking. In the next three chapters, SoS engineering methodologies are presented to operationalize these aspects of SoS thinking. In Chapter 3, a preferences construction methodology is developed to create value system models in order to obtain preferences from values. In Chapter 4, an agent-based framework is proposed to generate agent-based models of competitive and cooperative behaviour under conflict. Preferences that were constructed using the methodology presented in Chapter 3 serve as inputs to the models of strategic interactions demonstrated in Chapter 4. Finally, in Chapter 5, a SoS engineering methodology is synthesized for risk management in which risk and strategic analyses are linked in a feedback system. Altogether, the foregoing developments constitute a SoS engineering framework for policy development.

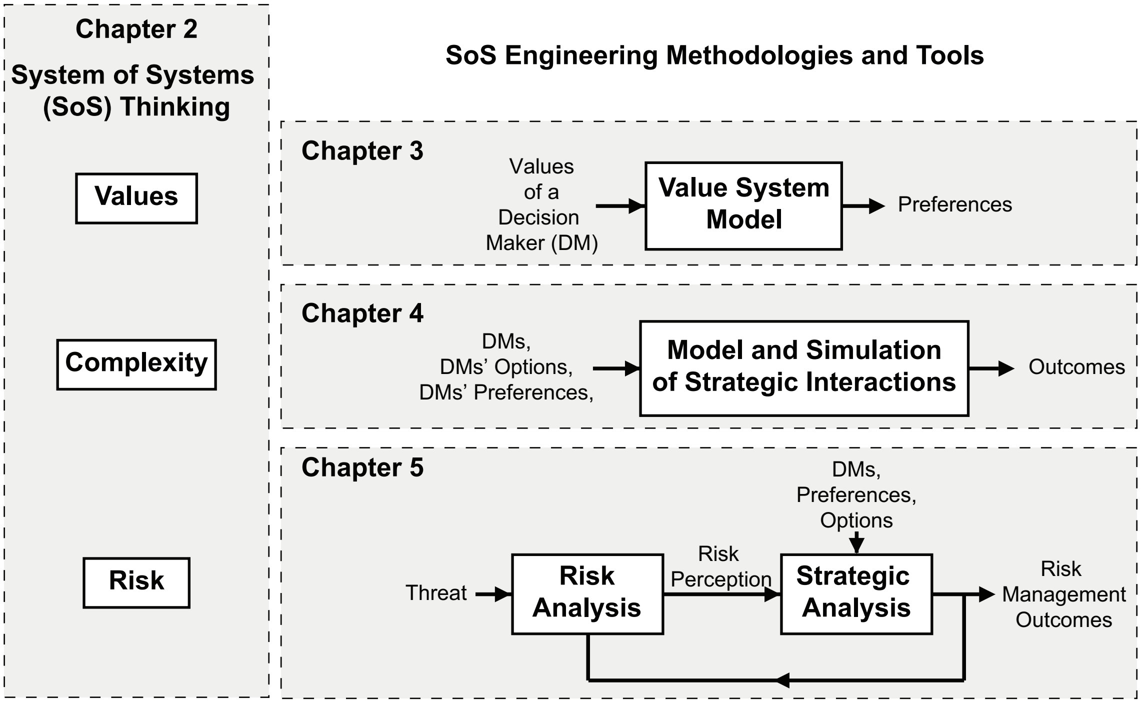


Figure 1.2: Organization of this thesis.

The framework and suite of methodologies provide participants, in particular, DMs, policy makers and analysts, with tools to analyze SoS challenges. Fundamentally, the research focuses on the challenges and opportunities imbued in cooperative-competitive relationships. Through these research endeavours, it is hoped that participants will be able to view a SoS from their own and others' perspectives, to increase the value-added of hard thinking on their own and others' values, and to design policy solutions that are integrative, adaptive, and ethical. The models presented in this thesis are prescriptive models which attempt to describe the conflict situation and to inform participants on what should be done to reach better outcomes. While the arguments in this thesis does not state specific policy recommendations, it is shown through application of the methodologies that analysts, DMs and participants in a conflict can formulate SoS models to systematically think about values, complexity and risk. Moreover, it is argued that the results of simulations can be useful in decision making for strategic policy development and responsible risk management.

The main purpose of the results that are presented in this thesis is illustrative rather than representative. In order to bring these models into the arena of real-world policymaking and conflict situations, empirical and field investigations must be undertaken in tandem with modeling and simulation studies so that the effective solution space can be constrained and policy recommendations can be directed. To conclude this body of work, the last chapter discusses the main contributions of this thesis and consequently, future research directions to further advance the current state of knowledge and practice of SoS engineering for policy development. ■

Chapter 2

System of Systems Thinking about Policy Development

In this chapter, the main objective is to devise a policy development framework for addressing SoS problems, which may be global in nature, based on a review of SoS thinking in which value systems, complex systems, and risk management are foundational pillars. In Section 2.1, motivation for this work is presented. In Section 2.2, the rationale for using a SoS approach in policy development is discussed. The new contribution of this chapter is a policy development framework introduced in Section 2.3. Strategic and operational methods for modeling and analyzing value systems, complex systems, and risk are also explored. An illustrative example of modeling the global food system in Section 2.4 argues for the use of a SoS approach in practice to guide policy development. Some of the research contained in this chapter was presented earlier by Hipel, Fang and Heng (2010).

2.1 Motivation

Crises of energy, water, and food security are matters of international scope. Everyone is affected because everyone is connected through the natural and man-made systems that provide us with the necessities to sustain our living. The connections among systems are complex and ultimately it is these interactions which may create emerging crises. As argued by Homer-Dixon (2006) and others (Glenn et al., 2008), these complex problems are highly interconnected and are focusing their highly destructive power on an increasingly vulnerable and fragile world.

Our managed energy, water, and food systems are intertwined societal-technical systems that are heavily interconnected with the natural environment. They may be considered as “systems of systems”. These systems clearly satisfy Maier’s (1998) two necessary criteria to designate a SoS: (1) operational independence of the components and (2) managerial independence of the components. Furthermore, a SoS may be geographically distributed, display emergent behaviour and undergo evolutionary development, self-organization and adaptation (Sage and Cuppan, 2001; Sage and Biemer, 2007). Systems of systems, like our managed energy, water and food systems, contain many innovations and of course, are beneficial to our societies. However, they are also subject to external and internal risks and conflicts.

Factors, such as declining oil supplies, limited fresh water, and degrading arable land are natural constraints to which humans must learn to adapt in managing a finite energy-water-food supply. However, the bulk of our problems are not only imposed by natural systems, but also by the systems and institutions that have been created by humans. Specifically, in our experience of managing food systems, crises emerge from a complex web of factors stemming from environmental conditions, poverty, agricultural and economic policies and management (Eicher, 1982; Berry, 1984; Alexandratos, 1999; Friedman, 2002). Moreover, interdependencies have increased over time between countries now labeled as Low Income Food Deficit Countries (LIFDC) and other nations. The overall system seems to be extremely vulnerable to price shocks, causes of which have been debated in the media and spurred many researchers to investigate the pronounced price increases in 2008 objectively (Abbott et al., 2008; Headey and Fan, 2008; Clapp and Cohen, 2009). Implementation of long-term solutions to the global food crisis will not be simple.

The main challenge that we face in managing a SoS is responsibly dealing with unpredictable and uncertain outcomes of policies, and conflicts that arise among multiple participants. Unpredictability and uncertainty necessitate effective risk management. Moreover, in any situation where there are multiple participants, which is an inherent characteristic of a SoS, there will be multiple conflicting value sets and multiple objectives (Hipel and Fang, 2005). Policy decisions can have a deleterious and irreversible impact on people's livelihoods and their environments. With so many stakeholders and competing interests at loggerheads with one another, coordination of decisions in the system is a major challenge. When following a SoS approach, one desires to mitigate the risks associated with policies and to resolve conflicts with operational methods.

2.2 System of systems thinking

System of systems thinking is a paradigm shift, succinctly stated by Hipel et al. (2007), “from a disciplinary to a multidisciplinary outlook, from a mass production to a mass customization focus, from a steady state to a real-time perspective, and from an optimal to an adaptive approach.” In policy making, one should attempt to live with complexity and uncertainty. That is, large-scale system problems need not be treated in a homogenous and deterministic manner. Rather, we should continuously search for an efficient state of fairness and balance in society, which is often an unknown, dynamic target (Saul, 2008).

The point of departure from conventional systems thinking to a SoS perspective is that components in a system are by themselves individual systems that are autonomous, heterogeneous, and complex (Sage and Biemer, 2007; Gorod et al., 2008; Jamshidi, 2009). With significant advances in understanding systems science (Warfield, 2006), from chaos (Gleick, 1987) to complexity (Lewin, 1992), and across disciplinary boundaries from sociology to engineering (Rouse, 2003; Braha et al., 2006; Epstein, 2006; Miller and Page, 2007), SoS thinking, in a way, naturally evolved to respond to increasingly complex problems and systems (e.g. service systems (Tien, 2008; Tien and Goldschmidt-Clermont, 2009)).

For policy development, the purpose of utilizing a formalized SoS approach is to harness complexity (Axelrod and Cohen, 2000) inherent in large-scale, multi-disciplinary issues and to address the composite SoS problems that arise from interactions among environmental, societal, intelligent, and integrated systems (Hipel and Fang, 2005; Hipel et al., 2007, 2009). In so doing, it is argued that a SoS approach must involve deep consideration of values and ethics, complex systems, and risk, in order to address problems in an integrative, adaptive and ethical manner.

2.2.1 Values and ethics

All SoS are inhabited by multiple participants with multiple objectives (Hipel and Fang, 2005). Hence, a SoS approach must take into account multiple, possibly conflicting, values to design and implement ethical policies. For example, water resources management faces many challenges that involve energy, services and infrastructure, industrial, and agricultural systems and corresponding stakeholders. Note that each individual system is operationally and managerially independent (Maier, 1998), thus water resources management may be considered a SoS. Numerous people, societies, and nations in our highly interconnected world face a looming water crisis as the world supply of fresh water becomes scarce due to climate change, pollution, exponential population growth and industrialization of developing countries such as China and India (Barlow, 2007). The SoS consists of many different participants (or agents) who are interacting synergistically to procure, consume and recycle water. Some of these participants are public water providers, private water vendors, and consumers ranging from individuals to transnational corporations, who rely upon the environment and energy to power water treatment technologies to sustain a continuous supply. Multiple objectives exist within and among the participants. For policy and decision makers who are tasked with managing water resources, systematic methods that are able to communicate the values and interests of all participants are needed to understand the complex behaviour of the overall system (Hipel et al., 2008), and hence, to design policies that reflect those values and ethically binds all participants to respect them.

Amid the variety of value systems of participants inhabiting a SoS, conflict is an inescapable condition due to the immense diversity of values and opinions. However, important links among their values inextricably connect participants to one another. The environmentalist desires a stable economy and the economist needs a clean environment (Wilson, 2002). To take an extremist stance is to deny the existence of the other and to prescribe the demise of oneself who depends on the other. In order to start understanding the global challenges such as climate change, which Wilson (2002) notes are too "complicated to be solved only by piety and an unyielding clash of good intentions," policy and decision makers need to seek out solutions that put aside moral superiority.

Moreover, managed SoS must be ethically maintained (Hipel and Fang, 2005). Ethics go beyond ambiguous moral commands that are open to interpretation and are insufficient to protect against the underlying forces that threaten the rights and freedoms of each participant. A universal ethical framework should be able to integrate different values and changing values, reflecting the reality of multiple cultures and beliefs, while maintaining the freedom of each individual. Clearly, current societal systems are not based on a universal ethical framework. Shrybman's (2001) commentary on the World Trade Organization (WTO) concludes that "if international investment rules are to foster, rather than undermine, our prospects for achieving environmental goals, they will have to be fundamentally overhauled." Good policies must be firmly based on the values of all stakeholders, not just a privileged minority, which persists unfairly in the global market, where rights are purposefully given to transnational corporations and no one else (McMurtry, 2002). The political landscape is much more diverse and policies should reflect that landscape; not only because it is ethical, but also because diversity fosters greater resilience (Newman and Dale, 2005).

2.2.2 Complex systems

Kotov (1997) defines a SoS as a large scale concurrent and distributed system that is comprised of complex systems. It is also accepted that a SoS involves complex adaptive systems (Hipel et al., 2009), which exhibit emergent behaviour, evolutionary development, self-organization and adaptation (Sage and Biemer, 2007). Consider the global food system, which consists of agricultural systems, food producers, processors, packagers, consumers, distribution networks, trade agreements, agricultural policies, markets and biotechnologies. There is no shortage of problems, as well as many achievements, in the global food system, which exhibits a diverse landscape that changes and can be changed. In order to effectively govern in a SoS, we must understand how complex systems behave and how desired behaviour may be achieved.

Food price spikes in mid-2008, and subsequent world-wide violence, signaled a global food crisis (Dunphy, 2008; UN, 2008). Food commodity prices have become highly unpredictable. Based on the historical export prices of rice, wheat and maize from 1961 to 2008, shown in Figure 2.1, it is difficult to predict future prices due to price spikes and high variability. Huchet-Bourdon (2011) confirms that the price volatilities for wheat and rice were higher in 2006-2010 than in both the 1990s and 1970s. A significant part of the variability, however, may be explained by the measurement of food cost in terms of American dollars, as oppose to a more stable currency such as gold (Fieguth, 2013).

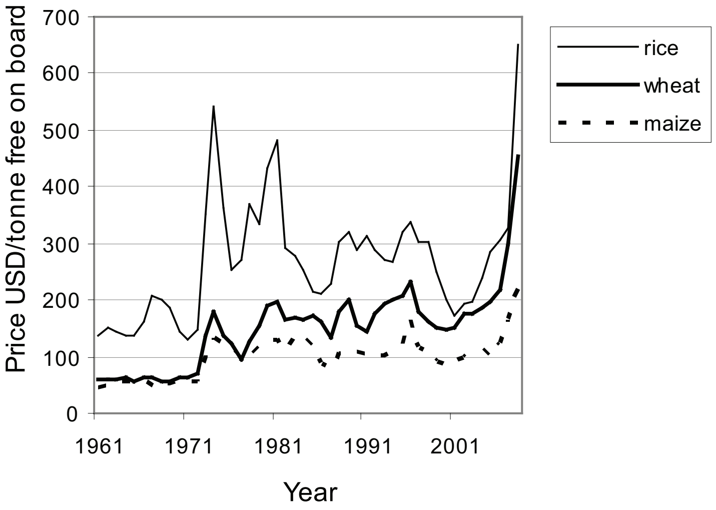


Figure 2.1: Export prices of rice, wheat and maize (1961-2008). (IRRI, 2009; data included in Appendix A).

Moreover, the issues which arise in the system—paradoxically, obesity (stuffed) and malnutrition (starved) (Patel, 2007)—are complex due to the many interacting factors which cannot be resolved in a compartmentalized manner. Solutions must also be devised in an equally complex manner, i.e., via an integrative and adaptive systems methodology which addresses issues concurrently and flexibly. Integration leads to greater connectivity and efficiency, while adaptation leads to greater value and responsiveness (Tien, 2008).

Adaptation is possible through complexity. Complexity is increased by variation and interactions, which is needed for adaptation and selection processes in which an entity changes in response to other entities and its environment to become fitter for survival. Participants are capable of adapting independently in terms of form (what they are) and function (what they do). Form and function together create a variety of available strategies, which are conditional sequences of actions that participants undertake to achieve their objectives. The adaptation of participants, such as farmers, consumers, and transnational food corporations, will depend on cues from each other and other stakeholders, as well as from the environment. This can present opportunities as well as barriers. It is important for policy and decision makers to understand the interlocking processes of adaptation in order to guide productive institutional reforms that make use of complexity.

2.2.3 Risk

Many SoS are intimately reliant on the natural environment, and thus can be adversely affected by natural disasters such as floods and droughts. All SoS should manage risks in their uncertain and unpredictable environments. Natural events such as earthquakes and hurricanes occur and are beyond the control of any human-made system. The Asian Tsunami in 2004 and Hurricane Katrina in 2005 are ranked among the most devastating disasters in the 21st century. However, a close look at the case of Hurricane Katrina reveals that the disastrous effects were due to manmade errors in the 100-year flood protection system (Van Heerden and Bryan, 2006) and faulty engineering solutions that were misguided by conflicting priorities of different stakeholders, such as the US Army Corps of Engineers, politicians, and other commercial-interest groups in the oil and shipping industry (Grunwald, 2007).

More frequently, disasters occur and are made worse by societal systems that put people and other systems at greater risk (Wisner et al., 2004). Thus, in order to fully address vulnerabilities and mitigate risk factors, a more balanced assessment that redresses the dominant attention on technical factors in the natural environmental systems towards greater focus on social, political and economic factors in societal systems is required (Wisner et al., 2004).

Further, the interactions between nature and society through technology are also of concern. For example, mitigating the risks of natural disasters due to climate change goes far beyond understanding the science behind weather patterns, which is also an important component. It involves understanding the interactions among geophysical, biological and global human systems, which include food supply, infrastructure, health services, and water resources. Human development has significantly reduced the resilience of ecosystems, thereby making ecosystems and their biologically diverse populations more vulnerable to climate change (Parry et al., 2007). Moreover, marginalized populations in developing countries, who are caught in the social trap of poverty, are especially vulnerable to the impacts of climate change because of their constrained ability to adapt (Stern, 2007).

The final task of policy and decision makers is to select rules to enforce and strategies to implement policies that are within an acceptable risk tolerance. In the event of natural hazards or external shocks, it is hoped that they are also capable of reducing the risk of catastrophe and collapse and, instead, create opportunities for “catagenesis” through adaptation (Homer-Dixon, 2006). Characterization of risk with methods that delineate uncertain and unpredictable outcomes should be used to aid policy and decision making.

2.3 Policy development framework

Based on SoS thinking about values, complexity and risk, a policy development framework is proposed in this section. As an area for application, the challenge of achieving global food security is used to argue for SoS thinking and the usefulness of the proposed framework in policy development. The current food system is a product of globalization, which has generated great advancements, but has also created increasingly complex policy issues. The globalized economy has technically enabled countries to import food from around the world, thereby empowering people to enjoy a diverse diet and higher standard of living. However, the system is also rife with people suffering from obesity or hunger and malnutrition. In 2008, approximately 500 million adults were clinically obese (WHO, 2013). Moreover, childhood obesity is already an epidemic in some areas and on the rise in others (WHO, 2003). Based on 2010-2012 data, there were approximately 868 million undernourished persons worldwide (FAO, 2013). It is becoming increasingly recognized that these problems are systemic and must be resolved as a whole in the global food system (Patel, 2007).

Food security, as defined by the United Nations Food and Agriculture Organization (FAO) (2003), “exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life.” Global food security is the application of this concept internationally.

However, there is no central governing agency which is capable of ensuring global food security. Transnational corporations, through free-trade agreements, appear to wield unwarranted power to exploit the global food system (Nestle, 2007; Patel, 2007). In general, as Harmes (2004) explains in *The Return of the State*, corporations operate at the global level, while governments are constrained to the national level and cannot regulate international activities to ensure accountability to the public good. As a result, nation states have less control over matters of national security, such as financial or food security, in a globalized system where their economies are so tightly linked.

What is needed to effectively address our global challenges, are national and international policies that are systematically conceived to harness complexity rather than eliminate it, to mitigate and avoid risks instead of increasing them, and to respect the rights and freedoms of every human being, which are constantly being violated throughout the world today.

Current policy development is generally lacking in an approach that is cooperative, integrative, adaptive, firm and compassionate. The policy development framework, illustrated in Figure 2.2, seeks to fill this gap. In this framework, policy development is supported by the three pillars of a SoS approach: values and ethics, complexity, and risk. The role of policy development is to create integrative and adaptive international institutions and agreements in order to achieve good governance based on democratic principles to enforce regulations that protect the public and individual rights. Institutions and agreements should create and sustain an environment for integrative and adaptive management, so that participants in the system can meet their objectives and manage their risks according to their own value systems. However, since disputes or differences of opinion can arise even when you have good policies, a dispute resolution mechanism, designed to lead conflict in a positive direction, is also necessary in the design of all policies.

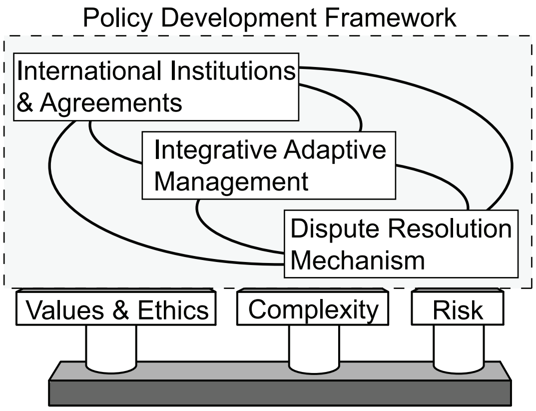


Figure 2.2: Policy development framework based on system of systems thinking.

While systems engineering is fundamentally a management technology to assist and support policy making, planning, decision making, and associated resource allocation or action deployment (Sage, 1992), a SoS approach provides strategic and operational methods to carry out creative problem-solving on our most pressing global problems, which involve multiple participants in interconnected complex systems.

2.3.1 Start with values

With systems engineering approaches, policy and decision makers can incorporate values into policy development and decision making in a systematic way. The performance of value assessments should lead to clearer communication of objectives, more transparency of value judgments in the selection of appropriate attributes, and better accounting of value tradeoffs in eliciting utility and preference information. As Hipel and Fang (2005) have previously pointed out, it is important to keep in mind that differences in value systems and underlying arguments of ethics and beliefs provide the basic fuel for igniting and maintaining conflict.

For conflict resolution, it is necessary to determine the value systems of each DM, and to subsequently analyze the strategic interactions among the decision makers. As in the Graph Model for Conflict Resolution (GMCR) (Fang et al., 1993; Inohara and Hipel, 2008), values can be assessed and conveniently translated into preferences using an option prioritization approach (Fang et al., 2003a, 2003b). Option prioritization mathematically derives preferences based on a set of lexicographic preference statements about options. The derived preferences of many stakeholders can be utilized in decision support systems (DSS) to model conflicts, which aids a DM in making an informed, and thus, better decision. In a SoS where there are multiple participants who may form a group, an aggregated preferences of a group of DMs can also be generated and integrated into a DSS for use in group decision making situations.

Since a DSS is only as good as the information that is provided to it, it is important to use a systematic method, such as the one presented by Keeney (1992) and Keeney and Raiffa (1976, 1993), to understand and operationalize value systems with a value model, also referred to as an objective function. In this method, objectives are identified and hierarchically structured so that fundamental objectives are linked to lower means-ends objectives. Attributes are selected to measure the achievement of each objective. The selection of attributes involves value judgments, which should be clearly communicated and debated in policy making circles.

Using the identified objectives and attributes, a value model quantifies the objectives mathematically by assigning either utility (quantitative) (Von Neumann and Morgenstern, 1944, 1953; Keeney and Raiffa, 1976, 1993) or ranking (nonquantitative) preference information (Howard, 1971; Fraser and Hipel, 1984; Fang et al., 1993). Put simply, an alternative with a higher utility or higher ranking is a more preferred alternative compared to one with lower utility or lower ranking. A value model describes the preference structure of a DM's value system, which is used to determine the relative desirability of consequences, and the overall preferences for alternatives. Using preference relations, which may be multiplicative, fuzzy, intuitionistic, linguistic, and possibly incomplete and uncertain, depending on the availability of information, it may be possible to derive a utility function which can be used to calculate the utility of any alternative, or at the least, to rank alternatives. Details on different preference relations are explained well by Xu (2007) and Xu and Chen (2008).

In order to formulate quantitative value models, a policy maker would need to determine value tradeoffs which are encountered in a given set of objectives. Value tradeoffs are necessary when objectives compete for limited resources. Thinking about value tradeoffs requires a judgment on exactly how much one or a group is willing to sacrifice in achieving one objective for a specified amount of gain in achieving another objective. Appropriate tradeoffs can then be encapsulated into a utility-based value model. Using a value model, it should be possible to obtain preferences. On the other hand nonquantitative preferences can be obtained using a weighting or prioritization algorithm (Fang et al. 2003a). Preferences can be used to evaluate alternatives. More importantly, hard thinking about values and translating them into objectives can aid in the creative process of generating alternatives that complement the modeled value systems.

2.3.2 Navigate through the complexity

In modeling complex adaptive systems, the focus is on how local interactions create global structures and patterns. An immense amount of research effort has been and continues to be put into the creation and validation of new computational models (Epstein, 2006; Miller and Page, 2007). Creating a model is by no means a simple task. However, using a well-defined approach ensures that the constructed model is transparent, clear and consistent. In a way, a model serves as a communication tool. Moreover, a model may help policy makers navigate through increasingly complex policy issues. In a SoS, emergence is an unpredictable behaviour, and there is no certainty that a model is correct. However, a generalized model can be used to test an ensemble of policies in multiple scenarios which would require many different model deployments. Simulating multi-agent systems is a way of representing many possible realities based on a single model constructed by the designer (Casti, 1997). It can be useful in policy analysis in order to understand emergent properties and the consequences of interacting policies. Results can lead to more structured and deeper analysis.

Using a SoS approach, an analyst can thoroughly test a policy design before it is put into place and adaptively improve it over time, as value systems and environments change. The main steps of simulating policies in a complex SoS environment are shown in the process diagram in Figure 2.3. The first step is to identify the policy issue with a problem definition which may have different facets depending on the perspectives of participants who are involved in the issue. Additionally, a delineation of the SoS of interest and a clear statement of what the analysis intends to achieve should guide the next steps. Once problems have been

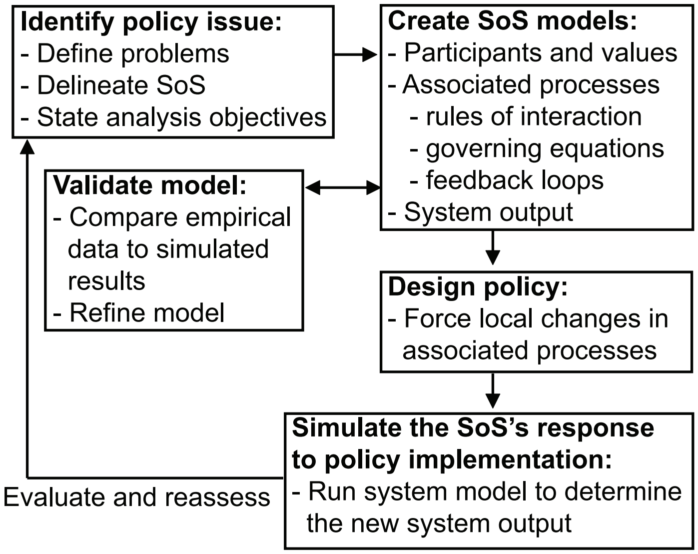


Figure 2.3: A systematic method for testing policies prior to implementation.

identified, the next step is to create SoS models based on participants' perspectives and values. The associated processes are formalized using rules of interactions, governing equations, and feedback loops. A modeler needs to specify the system output of interest, which is relevant in characterizing the behaviour or performance of the SoS. System output signals are also related to the attributes that are selected to measure the achievement of DMs' objectives. A model should be verified against empirical data to validate and refine it.

The next step is to design a policy, which is any mechanism including laws or regulations, which involves the forcing of local changes in the associated processes. A policy, such as a ban on a particular substance or a tax for a certain commodity, would change the strategic interactions among participants. At the local level, the modeler would modify the rules of interactions or the governing equations to reflect the effect of the new policy. The final step is to simulate the system response to the policy implementation, which involves running an analysis or simulation to determine the new system output. As the model output is only as credible as the assumptions that were made, several iterations over a large ensemble of plausible system representations may be necessary in order to observe patterns that are generally true, which is the purpose of exploratory modeling and analysis (Agusdinata, 2008). Hence, the process is iterative to evaluate the simulation results and reassess the original policy issues, objectives, and assumptions, as well as to adjust the model as new information and insights become available.

2.3.3 Design for reliability, robustness and resiliency

Understanding risk and managing it are an integral part of a SoS approach and should be undertaken in decision making and policy development (Haimes, 2009a). Failing to assess the risk of a new policy ignores an essential dimension of the problem, which is interconnected with the ethics and complexity of the SoS. Participants' value systems determine what is and is not an acceptable risk. Haimes (2009a) stresses the importance of considering multiple objectives in risk management, and hence, uses a multiple criteria decision analysis (MCDA) approach. Moreover, the complexity of a SoS is often intertwined with uncertainty, in that the dynamic behaviour of a complex entity is rarely deterministic, and often unpredictable. Fortunately, there exists a plethora of formal mathematical methods that have been developed for risk assessment. Uncertainty can be represented using probability, belief functions, possibility rankings, and plausibility measures (Halpern, 2005), as well as fuzzy sets (Zadeh, 1973), grey sets (Deng, 1989), rough sets (Greco et al., 2001), information gap theory (Ben-Haim, 2006) and other formal methods.

Hashimoto et al. (1982) developed three risk-related criteria for evaluating the performance of water resource systems which include: 1) reliability: how likely a system is to fail, 2) resiliency: how quickly it recovers from failure, and 3) vulnerability: how severe the consequences of failure may be. Okada (2005) created a conceptual framework for integrated disaster risk management, referred to as Vitae Systems principles, which are: 1) survivability: aim for resilience, defined as surviving shocks with least probable damage or least severe damage; 2) vitality: encourage each individual to be resourceful and to lead a healthy and fulfilling life, and 3) conviviality: emphasize communication and cooperation within and among communities (Hipel et al., 2011b).

An important fact to keep in mind is that a SoS approach is not only concerned with the physical infrastructure, such as dams, roads and pipelines, but also with social, financial, and political infrastructure and governance. Volatile financial markets and unresponsive or corrupt governments are more responsible for disasters than the environmental systems from which they may originate. Therefore, the goal of risk management for a SoS is two-fold: 1) to assess and control the hazards contained in a risk domain with desired reliability and robustness, and 2) to understand the vulnerabilities of societal-technical systems to uncertain and unpredictable hazards that propagate through environmental systems, and to build up resilience in both societal and technical capacities. Haimes et al. (2008) stress that these objectives may be conflicting and that there needs to be a balance of prevention, deterrence and protection on one hand, and resilience on the other.

Moreover, Leiss (2001) points out the need for risk issue management, which refers to the resolution of risk controversies. Such a task requires a system-level perspective to effectively communicate risks to all stakeholders and to design and implement appropriate procedures and policies. At the core of a risk controversy are competing interests of several stakeholders that attempt to define or control the course of social action with respect to perceived hazards (Leiss 2001). Hatfield and Hipel (2002) suggest that many cases of controversy around risk-based decisions and assessments can be traced to implicit and undocumented value-based decisions. What policy makers have to realize and communicate effectively to the public and other decision makers is that uncertainty will always exist. Effective risk issue management is achieved by confronting the existence and implication of persistent uncertainties in a timely manner, with open dialogue at the interface of science and public policy (Leiss, 2001).

Altogether, the basic steps of risk management for policy development are illustrated in Figure 2.4. First, risk and reliability assessments are performed to determine the hazards that lead to failures in the SoS and to search for ways of reducing them. The hazards are delineated with uncertain and unpredictable variables, which are inputs to the SoS model. Then, using the general system models of the SoS under study, multiple risk scenarios are explored to create a spectrum of specific system realizations. Through the analysis of the system output, consequences are reasoned based on patterns in the system's behaviour. Since risk management should be a continuous and adaptive process, a feedback loop is shown to inject resilience into the system with adaptive and integrative policy designs. Here, policy designs are considered adaptive if they are flexible enough to respond effectively to different scenarios. They are considered integrative if, with cooperation, they utilize system resources

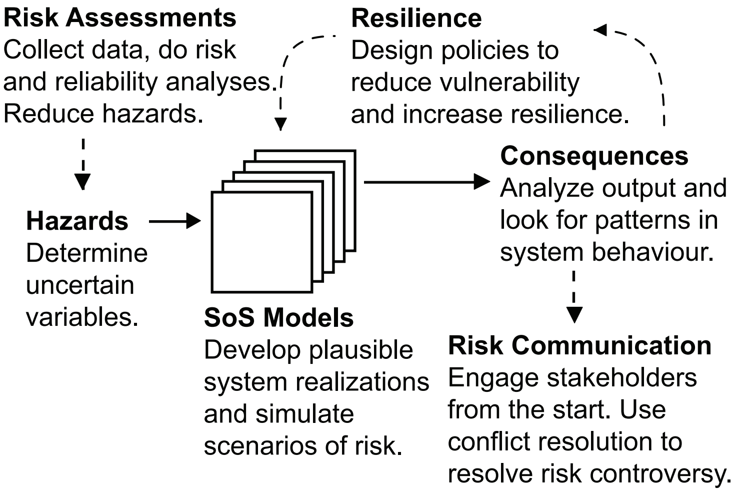


Figure 2.4: An iterative design approach to risk management

efficiently and effectively. Risk communication also plays a vital role in risk management to engage stakeholders throughout the process so that uncertain consequences are better understood. With a SoS approach in policy development and the supporting tools of systems engineering, multidisciplinary dialogues, particularly among scientists, engineers, business leaders, the public and policy makers, can take place in order to tackle our global challenges.

2.4 Policy development for global food security

In this section, a SoS model of the global food system is discussed to develop an understanding of the system and to provide insights into policy development for global food security using SoS thinking. Specifically, the policy issue and the general SoS context are presented.

With the sharp increase in global prices of staple food commodities such as rice, corn and soybean in April 2008, civil unrest and violence linked to the soaring prices occurred around the world (FAO, 2008). The situation was called a global food crisis. Unlike a natural disaster, experts knew that it could not be turned around quickly due to its complexity (Ki-moon, 2008). Unfortunately, as the media shifted its attention to the global financial crisis and newly emerging conflicts, the food crisis failed to grasp the attention that it deserved at the year’s end. It remains as a sustained crisis that should rank high on every country’s national security agenda. Former US President George W. Bush (2001) hit the point home when he stated: “Can you imagine a country that was unable to grow enough food to feed its people? It would be a nation subject to international pressure. It would be a nation at risk. And so, when we’re talking about American agriculture, we’re really talking about a national security issue.” In a highly connected world, it is a global security issue. In order to secure a nutritious food supply for all nations and individuals, fundamental changes to the agribusiness infrastructure, and supporting political and economic systems are required. It is a daunting task and requires the conscious effort of many people over a long period of time. In the same way that Singapore overhauled its education system to fix a 40% failure rate at the primary level of schooling in the 1970s (Chuen, 2008), rethinking of the global food system is necessary to fix multiple failings of the food system that manifest themselves in the form of famine and lost livelihoods, environmental degradation and land loss, as well as obesity, malnutrition, and human health impacts of an industrially processed food diet (Shiva, 2000; Heintzman and Solomon, 2004; Pawlick, 2006; Pfeiffer, 2006; Nestle, 2007; Patel 2007; Pollan, 2008). These are the policy issues.

2.4.1 The global food system as a system of systems

In the evolution of natural and man-made systems, the interconnectedness of components, and thus the overall complexity of the system, naturally increases over time. The natural environment and man-made energy, water and food systems demonstrate very high complexity. Agriculture is essentially the management of a secure food supply. From its simple beginnings of subsistence farming, it has evolved into a SoS that not only exploits environmental systems, but also utilizes large-scale production systems and international trade systems. The high-level interactions among these three groups of systems are illustrated in Figure 2.5. Environmental systems provide essential services and resource inputs to our production systems, which transform resources into useful products and discharge wastes back into the environment. The production systems are kept alive by demand for those useful products, which are supplied to international and domestic markets through sophisticated trade systems. In general, the health of the SoS depends on a balanced flow between systems. Figure 2.5 also shows the typical food supply chain which has elongated to capitalize

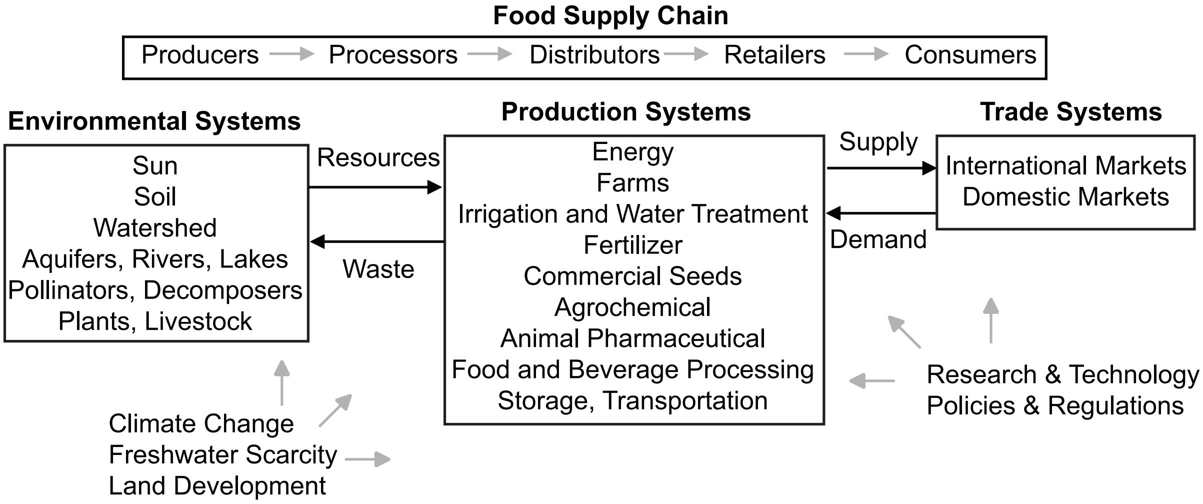


Figure 2.5: The global food system as a system of systems.

markets through value-added processes and distribution networks. The quality of food depends on accountability throughout the supply chain.

Agriculture is no longer just about cultivating enough food to live well. Today, it is foremost a business that sells commodities in a market to the highest bidder and seeks to maximize profit and not necessarily to feed the entire world's population. The global food system is dominated by oligopolies consisting of giant agribusiness corporations that control seeds, chemicals, processing, and distribution (ETC Group, 2005; Pfeiffer, 2006). Whether the internal power concentration among large corporations allows the global food system to meet multiple objectives of small-scale and industrialized farming is a concern. Recognizing that conflicting objectives exist suggests the need for greater integration of small-scale farming values in international negotiations. Meanwhile, external pressures such as climate change, freshwater scarcity, and land development threaten the stability and resilience of the global food system. Research and technology, and policies and regulations are depicted as external counter measures that attempt to counteract the external pressures and to manage internal struggles.

2.4.2 The global food system as a complex adaptive system

Using Gunderson and Holling's (2002) model of the adaptive cycle of complex adaptive systems, the adaptive cycle of the global food system as it exists today is plotted in Figure 2.6. The purpose of this model is to supplement the discussion of global food security with a narrative on its resilience. Only a few researchers, such as Le Vallee (2008) who studied food system resilience in Belize, link resilience research and food studies. Figure 2.6 hypothesizes a model to reflect global-scale food system dynamics. In future work, this hypothesis would need to be further specified in order to be able to disprove, as per the scientific method, its validity with empirical data or expert knowledge. The horizontal axis is connectedness in the system and the vertical axis is abundance, which is the inherent potential of the system to feed the world's population. In the growth phase, new technologies and processes are introduced with promises of higher yields and efficiency. The modernization of agriculture has been the driving force for increased exploitation of the earth's natural resources, which has resulted in an immense abundance of food. In an ideal conservation stage, the population stabilizes and food production and distribution is sustained to feed this population.

However, the reality is that we are struggling to maintain production levels and increases that were gained through modernization. In fact, Shiva (2000) argues that the growth in

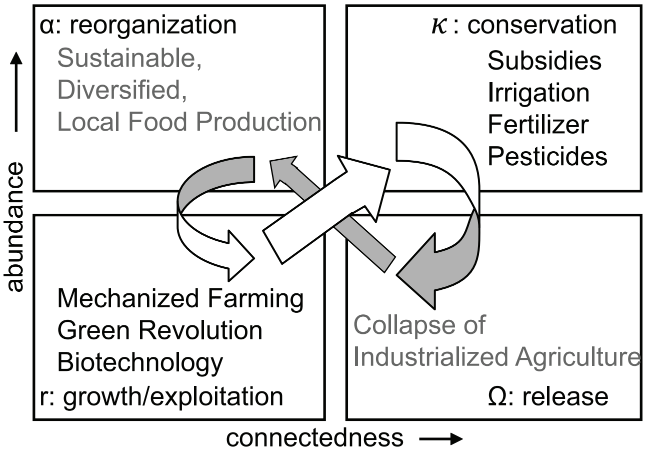


Figure 2.6: Depiction of the global food system's current adaptive cycle, consisting of four phases, which are growth or exploitation (r), conservation (κ), release (Ω), and reorganization (α) (Gunderson and Holling 2002).

productivity was an illusion that masked massive theft from nature and the poor. To maintain this growth state of the cycle, countries have created subsidy programs and farmers have become dependent on energy-intensive inputs and operations such as irrigation, chemical fertilizers and pesticides. During this phase, connectedness and abundance are at its highest and it is arguably the phase in which the global food system is currently functioning. The final two phases of release and reorganization are imminent. Pfeiffer (2006) connects the decline of the oil age to the collapse of modern industrial agriculture and points to North Korea as an example of how destructive the collapse will be on society and the irreversibility of its degeneration. At the core of the global food crisis, it can be understood that the high connectedness of industrial and trade systems coupled with the unsustainable resource pathways through the environmental systems resulted in incredible vulnerabilities and sensitivities to economic disturbances, which may not have the same destabilizing effects on a loosely connected or resilient system. The crisis is a signal to policy makers that the global food system is both getting ready and is already in the process of transitioning from the conservation phase to the release phase of its adaptive cycle.

Failure of the global food system could very well lead to the total collapse of society. When faced with a cascading crisis, there is not only the possibility of collapse, but there is also the opportunity to rebound and become even better (Homer-Dixon, 2006). As Kingdom (1995) recognized, crises can open up “windows of opportunity” if they are coupled with available solutions and a favourable political climate in which the time is right for change and the leadership can take action. However, available solutions should be tested before they are implemented. This is the purpose of using a SoS approach to solve large-scale system problems. Further investigation using a SoS approach in achieving global food security is needed to systematically design and test policies. Rigorous and in-depth analysis of value systems, complexity, and risks in the global food system should be undertaken to guide policy development and decision making to achieve global food security.

2.5 Summary of contributions

In this chapter, a policy development framework in Figure 2.2 was designed based on a review of SoS thinking. System of systems thinking involves deep consideration of value systems of participants to design ethical policies and resolve conflicts. An understanding of complex systems and how to utilize complexity is sorely needed to create integrative and adaptive institutions and agreements. Finally, risks should be managed in the process of policy development. Current and future generations are faced with complex global challenges in their journey towards achieving general well-being and security for all. The interconnectedness of natural, societal and technological systems means that DMs and policy makers must understand the SoS which they influence, as a whole, in order to achieve their desired outcomes and avoid unintended consequences.

In order to address SoS challenges, three research needs were identified. The first is the basic need to understand different value systems and to create a universal ethical framework with dispute resolution mechanisms to develop policy. Second, systematic methods are required to understand and utilize complexity towards productive ends. Third, new ways to engage with uncertainty and unpredictability are needed in order to plan and be prepared for shocks and respond gracefully to crises. Regardless of one's role in a SoS, each participant, from the lowest to the highest level, should be cognizant of the system perspective in order to fully understand one's role and how to best act in that role. That is a challenge for all, especially for DMs whose decisions in policy development invariably trickle down to affect the everyday lives of many others. This responsibility should be undertaken with an approach that is cooperative, integrative, adaptive, firm and compassionate. Hence, a SoS approach was proposed for policy makers who face increasingly complex policy challenges in a SoS. Formalized procedures for modeling values systems, complex adaptive systems, and uncertain and unpredictable risks were discussed.

Finally, it is argued that understanding of the global food system as a SoS is needed to achieve global food security. The strong links among environmental, production and trade systems provided an argument for acknowledging the interrelationships among trade and agricultural policies and their effects on the environment and people's livelihoods. In order to address complex global challenges, such as the global food and financial crises, a policy development framework based on values and ethics, risks, and complexity was introduced. The framework is a guide for policy makers in reforming institutions and agreements, fostering an environment for integrative and adaptive management, and designing effective dispute resolution mechanisms.

As we tackle the world's problems, there is a tremendous opportunity to generate solutions, including national and international policies and institutions, which are formally tested and evaluated before they are implemented. In the next chapters, novel SoS engineering methodologies are developed to operationalize the proposed policy development framework. ■

Chapter 3

Values and Policy Design

In this chapter, a methodology is developed to obtain ordinal preferences from values. Preferences are required inputs to decision and conflict analyses. Dynamic preferences construction is needed for an agent-based model and simulation (ABMS) platform that utilizes GMCR solution concepts in agents' decision making rules (Bristow et al., 2012b, 2013a). This chapter presents the development of dynamic preferences which can be used in the aforementioned agent-based framework. Moreover, the simulation results using the agent-based framework demonstrate the effects of different value judgments on the evolution of a conflict. The proposed methodology builds upon foundational work of Keeney (1992) and Saaty (1980). The new contributions are methods to construct preferences in the context of a conflict and to dynamically generate preferences which can be inputted into an agent-based model.

Section 3.1 provides the motivation for the work and Section 3.2 outlines relevant literature on eliciting preferences. In Section 3.3, the proposed methodology is introduced. Then, in Section 3.4, the methodology is applied to a theoretical multiple participant CPR dilemma, for which conflict dynamics are simulated in an ABMS platform. To demonstrate the influence of values on outcomes, strategic interactions are simulated for agents who employ a decision rule, which is based on Nash stability (Nash, 1950, 1951; Fang et al., 1993; Bristow et al., 2013a). Moreover, a sensitivity analysis is undertaken to demonstrate the sensitivity of an outcome to value system inputs. Section 3.5 concludes this chapter with a summary of contributions and implications on realizing strategic governance in a SoS. The first version of the proposed preferences construction methodology was presented at the 2012 IEEE International Conference on Systems, Man and Cybernetics (Bristow et al., 2012a). Some of the research in this chapter is also reported by Bristow et al. (2013b).

3.1 Motivation

Value-laden conflicts are at the heart of many challenges that humans need to address when at least two systems want to coexist. Human-made systems come into conflict with the Earth's interconnected systems when they perturb the Earth's natural cycles. Climate is interconnected with water (Bates et al., 2008), forests (Allen et al., 2010) and fisheries (Brander, 2007), for example, and their natural cycles are threatened by pollution, over-exploitation and environmental changes that are enabled by new technology, global markets and inadequate governance structures. Moreover, human systems that take from common-pool resources are naturally forced into conflict with one another when limits on these resources are almost reached. As an example, hydrocarbon fuel-powered systems are overtaxing the atmosphere with carbon emissions, thereby disturbing the carbon cycle and forcing a response from the Earth's climate systems; climate wars are expected to ensue (Dyer, 2008). Resolving conflicts such as these towards cooperation rather than destruction will require a deeper look into values. Conflict resolution methods must reflect the value systems of DMs. At a SoS level, strategic governance involves understanding of agents' value systems, which is needed to influence agents to make decisions leading towards cooperative outcomes that promote harmonious coexistence of systems.

Preferences are necessary for DMs to choose from among two or more alternatives, strategies, or courses of action. They can be mathematically defined but are fundamentally based on subjective constructs such as values, attitudes, perceptions, and risk tolerances. Moreover, evidence shows that DMs construct their preferences in the process of making a judgment and according to the context of the decision at hand (Lichtenstein and Slovic, 2006). As agent-based models try to simulate human-like decision making processes, one needs to codify agents' preferences according to values. Moreover, a process to construct preferences dynamically in response to influencing factors within the context of the simulated situation is needed. The objective of this work is to develop a methodology for meaningfully determining ordinal preferences over states of a conflict (also referred to as outcomes or scenarios) according to DMs' internalized value systems, in conjunction with influencing external factors, such as rewards and penalties.

The contributions of this chapter are 1) a formalized methodology for constructing preferences dependent on value systems, 2) integration of dynamic preferences construction with an agent-based framework that utilizes GMCR, and 3) advancing agent-based modeling and simulation techniques for systematic policy making. In order to simulate the evolution of a conflict, preferences of DMs need to be generated such that DMs can evaluate the consequences of alternative options and select a course of action that aligns with their values. Thus, a method is proposed to capture preferences over a large number of states in a conflict based on a value system that is specific to a particular DM. Moreover, preferences are dynamic in the sense that they are responsive to interactions with other agents and parameters such as benefits, costs, rewards and penalties that can change over time. The preferences construction method is operationalized for utilization in an agent-based modeling platform.

3.2 Relevant literature

Seminal research in utility theory (Von Neumann and Morgenstern, 1944, 1953), value-focused thinking (VFT) (Keeney, 1992), and multi-criteria decision making in general (Keeney and Raiffa, 1976, 1993; Saaty, 1980; Hobbs and Meier, 2000) have guided the development of the methodology presented in this chapter. Although there are many different approaches to multi-criteria decision making, a particular set of concepts was selected to formulate a framework for generating preferences according to requirements of an agent-based modeling platform in which agents use GMCR models to make decisions. In this section, utility approaches are compared to relative weighting and prioritization methods to obtain preferences. Since GMCR only necessitates ordinal information of preferences, a relative method rather than a utility approach is co-opted; however, a utility approach may be warranted in future work to consider strength of preference and uncertainty of consequences.

3.2.1 Utility

Utility is a measurement of value of something to an individual. When one item has more, equal or less utility than another, it is more, equally or less preferred than the other, respectively. Ordering two or more items based on their utility delineates an individual’s preferences. Von Neumann and Morgenstern (1944, 1953) proposed that rational agents have cardinal utility functions that satisfy axioms of completeness, transitivity, continuity and independence. Rational agents maximize expected utility calculated over all of the possible outcomes of a decision. Obtaining utility functions, however, requires hard thinking about how much value an individual derives from one outcome under consideration over others.

Keeney (1992) proposed a methodology for DMs to systematically think about what is really important and to translate what one values into measurable objectives characterized by quantitative attributes. Through value tradeoffs, that is, how many units of one attribute would one trade for an extra unit of another attribute, it is possible to derive a value function that maps the set of measured attributes of an outcome to a scalar number. Ordering outcomes on a common scale delineates an individual's preferences. More generally, within the framework of multiple attribute utility theory (Keeney and Raiffa, 1976, 1993), a DM can formulate a utility function over all attributes and calculate the expected utility over a distribution of outcomes. Finding the best course of action may be formulated as an optimization problem. However, it may be argued that human decision making is more about satisficing rather than optimizing (Simon, 1956). Also, decision making under conflict involves moves and countermoves among DMs according to their preferences as each person attempts to do as well as possible.

Utility approaches to delineate preferences, as proposed by von Neumann and Morgenstern (1944, 1953) and Keeney and Raiffa (1976, 1993), are notably rigorous, but can be time-consuming to calibrate. Instead of seeking an exact value of something, the measurement of which may contain bias and error and the absolute scale of which is subjective, procedures that extract relative rather than absolute information have been developed to elicit preferences.

3.2.2 Relative weighting and prioritization

DMs can construct preferences with the use of a relative value scale to derive weights on criteria where a higher weight means a greater influence on the final preference. For instance, the Analytic Hierarchy Process (AHP) (Saaty, 1980), and more generally, the Analytic Network Process (ANP) (Saaty and Vargas, 2006) structure the decision problem as a system of influencing components and calculate each component's relative importance, also called priority. Ordered priorities of alternatives can be interpreted as preferences. As in utility theory, AHP requires internal transitivity in the model. However, AHP allows DMs to express inconsistent assessments when making pair-wise comparison judgments of criteria and alternatives. The model, nonetheless, outputs transitive preferences over alternatives. The validity of weights can be checked against statements of the exact tradeoff that they imply (Hobbs and Meier, 2000). Ke et al. (2007, 2012a) proposed an AHP-modified approach to obtain DMs' preferences based on their judgments of relative influencing power and relative desirability of their own and others' options. In a similar hierarchical structure, Ke et al. (2012b) first relate criteria to actions and then to options, and subsequently use fuzzy logic operators to determine preference over states.

Compared to utility theory and analytic processes which are fundamentally quantitative methods, a natural method for constructing relative preferences based on nonquantitative information is lexicographic ordering. It is widely applied in practice, though criticized, because of its simplicity (Keeney and Raiffa, 1976, 1993). Lexicographic rules, however, can be employed in creative ways to order a very large set of outcomes which are differentiated over a relatively small set of attributes. The decision support system GMCR II allows DMs to specify preferences over states in lexicographical order based on a prioritized list of Boolean statements composed of conditions on DMs' options (Fang et al., 2003a). In contrast to multi-attribute utility theory, a lexicographical preference for one attribute over another implies that there is no amount that a DM would be willing to trade in exchange for the less preferred attribute. As such, a DM needs not exhaust energies in determining a value tradeoff and can efficiently compare alternatives to determine a preference.

Concepts and methods in the aforesaid literature are utilized to develop a methodology to construct agents' preferences dynamically according to their value systems in connection with rewards and penalties. The proposed methodology makes use of VFT and AHP to express a DM's value system. Different schemes to discern dominance of a state over others and to aggregate attributes into a payoff function are proposed to obtain preferences.

3.3 Proposed methodology for preferences construction

In this section, the preferences construction methodology, illustrated in Figure 3.1, is described. First, VFT is applied to translate values into objectives, define attributes to measure the achievement of objectives in relation to the states, also referred to as outcomes, of a GMCR model, and set criteria to determine satisfactory achievement of the objectives. Second, AHP is applied to calculate the relative importance of objectives and attributes from pair-wise comparisons of objectives and their attributes. Third, different comparison and aggregation schemes can be employed to order the states – in other words, to obtain preferences.

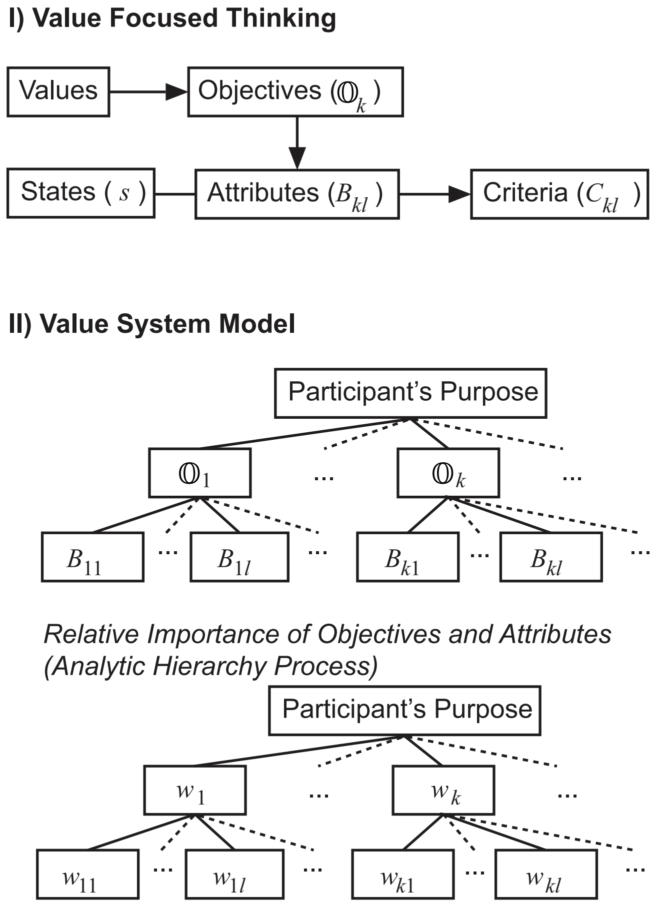
To apply the methodology, a decision context must be defined in some way. For the purposes in this thesis, a decision context is defined by a set of DMs denoted by N and their options in the set denoted by $O = \bigcup_{i \in N} O_i$, where $O_i = \{o_{ij} : j = 1,2,\dots,m_i\}$ is the set of options controlled by DM i, where o_{ij} is the jth option of DM i and m_i is the number of options available to DM i. A strategy for DM i is a mapping $g: O_i \rightarrow \{0,1\}$, such that

$$g(o_{ij}) = \begin{cases} 1 & if\ DM\ i\ selects\ option\ o_{ij}, for\ j = 1,2,\dots,m_i \\ 0 & otherwise \end{cases} \tag{3.1}$$

A state is a mapping $f: O \rightarrow \{0,1\}$, such that

$$f(o_{ij}) = \begin{cases} 1 & if\ DM\ i\ selects\ option\ o_{ij}, for\ j = 1,2,\dots,m_i, for\ i = 1,2,\dots,n \\ 0 & otherwise \end{cases} \tag{3.2}$$

where n is the number of DMs. Thus, a state s is expressed as an h-dimensional vector f_s, where $h = \sum_{i \in N} m_i$, and DM i's strategy corresponding to state s is an m_i-dimensional vector denoted by g_i^s. Let $S = \{s_1, s_2, \dots, s_{n_s}\}$ be the set of states in a decision context, where n_s is the number of feasible states.



III) Comparison and Aggregation Schemes

	Ordering by weighted sum	Lexicographical ordering
Compare states to a standard	*satisficer-weighting*	*satisficer-prioritization*
Compare states to each other	*optimizer-weighting*	*optimizer-prioritization*

Figure 3.1: Proposed preferences construction methodology consists of: I) applying VFT (Keeney, 1992) to determine objectives from values, attributes of states, and criteria; II) organizing objectives and attributes into a value system model in which relative importance of objectives and attributes are obtained through AHP (Saaty, 1980); III) ordering states using one of the four comparison and aggregation schemes.

A GMCR is a model of a conflict that takes the structure of a graph in which the nodes are the states and the arcs are unilateral movements between states that are controlled by a particular DM in the conflict. Hence, a GMCR model is completely specified by $G = \langle N, S, \{\succcurlyeq_i, A_i, i \in N\}\rangle$, where N is the set of DMs; S is the set of feasible states; $\succcurlyeq_i$ are relative preferences over pairs of feasible states for DM i such that $s_1 \succcurlyeq_i s_2$ means that DM i prefers s_1 to s_2 or is indifferent between the two states, and $A_i \subseteq S \times S$ is the set of directed arcs, which contain the movements in one step controlled by DM i.

The objective is to obtain preferences over states from the perspective of each DM, mathematically referred to as $\succcurlyeq_i$. Hence, the following steps should be carried out for each DM. First, fundamental objectives, attributes to measure performance of states, and criteria to assess fulfillment of objectives that are relevant to the decision context are obtained using VFT. Second, fundamental objectives, attributes, and criteria are organized into a value system and order of importance is obtained using AHP. Third, different schemes may be used to compare states to obtain ordinal preferences.

3.3.1 Value-focused thinking

Fundamental objectives that are relevant to the decision context are obtained using value-focused thinking (Keeney, 1992). Let $\mathbb{O}_k, k = 1,2,\dots,K$, be a set of fundamental objectives where K is the number of objectives. Each fundamental objective, $\mathbb{O}_k$, is considered as a goal which is independent of others. Then, features of each state in a decision context are mapped to attribute scales that are used to assess a score on the fulfillment of objectives. Let $B_{kl}, l = 1,2,\dots,L_k$, be the set of attributes to measure the degree to which objective $\mathbb{O}_k$ is met where L_k is the number of attributes associated with $\mathbb{O}_k$. An attribute, B_{kl} (the lth attribute of the kth objective), may be either quantitative or qualitative; in the case of a qualitative attribute, however, a numerical score is assigned to determine rank order on the attribute scale. Let b_{kl} indicate a specific amount of B_{kl}. An attribute may be a function of inherent features of a state, as well as external factors such as rewards and penalties set by authorities that are related to state features.

3.3.2 Value system and the analytic hierarchy process

A value system is defined as a set of fundamental objectives, with corresponding attributes and criteria, ordered according to importance. Ordering according to importance is performed through AHP from the perspective of each DM. The higher level values may be thought of as the DM's purpose or mission, to which the fundamental objectives contribute. Next, the contribution of each attribute to its corresponding fundamental objective is calculated using AHP. Input must be furnished by DMs, who are required to make value judgments in this step. For instance, DMs must specify through pair-wise comparisons the relative importance of fundamental objectives, as well as the relative importance of attributes in measuring achievement of a particular objective.

Given that Simon (1956) posited that decision making is more about satisficing than optimizing, DMs may be asked to set criteria for each attribute so that scores may be converted to a binary value where "1" means that the criterion is satisfied and "0" means that the criterion is not satisfied. A standard threshold value such as the mean of the scores may be used in place of a subjective criterion value if discrimination between high and low scores is objective. Criteria thresholds are only necessary when DMs are "satisficers," who determine the relative value of a state compared to a standard, rather than "optimizers," who determine the relative value of a state compared to another state.

3.3.3 Comparison and aggregation schemes

Finally, different methods may be invoked to order the states. Which method to invoke is based on two characteristics of a DM: 1) whether the DM is a satisficer or optimizer, and 2) whether the DM allows tradeoffs or prioritizes (i.e., no tradeoffs). Satisficers compare states to criteria thresholds; therefore, states that meet the same criteria are equally preferred. On the other hand, optimizers compare states to states; hence, states that perform the same on all attributes are equally preferred. In general, states that meet more criteria than other states, or that perform better on more attributes than others, are more preferred. When there is clearly not a best scenario, that is, states meet some criteria but fall short on others, or perform better on some attributes but worse on others, a DM may need to make a tradeoff or prioritize. If a DM allows tradeoffs, then a weighting scheme is applied. On the other hand, if no tradeoffs are allowed among attributes with different priority, then a prioritization scheme is employed. A tradeoff in the context of satisficing refers to how much is meeting one criterion worth compared to meeting another criterion and in the context of optimizing refers to how much an improvement on one attribute is worth compared to improvement on another attribute. It is important to note that the amounts by which criteria are met or the amounts of improvement on different attributes are not compared because they may not be quantitative. Instead, states are compared only by whether or not criteria are met or improvements are observed.

Satisficer-weighting scheme

In the satisficer-weighting scheme, the overall score for a state s is calculated as:

$$V^{SW}(s) = \sum_{k=1}^{K}\sum_{l=1}^{L_k} w_k w_{kl} c_{kl}(s) \tag{3.3}$$

$$c_{kl}(s) = \begin{cases} 0 & b_{kl}(s) < C_{kl} \\ 1 & b_{kl}(s) \geq C_{kl} \end{cases} \tag{3.4}$$

where w_k is the importance of the kth fundamental objective and w_{kl} is the importance of the lth attribute to the kth fundamental objective; $c_{kl}(s)$ takes the value of “1” or “0” depending on whether state s performs better or worse than the criterion/threshold point, C_{kl}, specified for the attribute B_{kl}. States are judged overall on the weighted sum of met criteria.

Satisficer-prioritization scheme

In the satisficer-prioritization scheme which is similar to a prioritization approach (Fang et al., 2003a), the overall score for a state s is calculated as:

$$V^{SP}(s) = \sum_{k=1}^{K}\sum_{l=1}^{L_k} 2^{r_{kl}} c_{kl}(s) \tag{3.5}$$

$$r_{kl} = \text{rank } (w_k w_{kl}) \tag{3.6}$$

where r_{kl} is the rank of the lth attribute of the kth fundamental objective, based on the DM’s value system. Note that if two attributes are ranked equally, then a one-to-one tradeoff between the two particular attributes occurs in this scheme. A state that meets more important criteria is more preferred.

Optimizer-weighting scheme

For the optimizer-weighting scheme, states are first compared pair-wise on the attribute level. Pair-wise attribute comparisons for each state to other states are rendered as follows. Let $Q \subseteq S$ represent the subset of states to be compared to state s. For $q \in Q$, let $d_{kl}(s, q)$ represent the pair-wise attribute comparison of state s to state q on the lth attribute of the kth fundamental objective:

$$d_{kl}(s,q) = \begin{cases} -1 & b_{kl}(s) < b_{kl}(q) \\ 0 & b_{kl}(s) = b_{kl}(q) \\ 1 & b_{kl}(s) > b_{kl}(q) \end{cases} \tag{3.7}$$

Then, $D_{kl}(s)$ is the cumulative performance difference, or dominance, of state s compared to all states in Q on the lth attribute of the kth fundamental objective. Hence,

$$D_{kl}(s) = \sum_{q \in Q} d_{kl}(s,q) \tag{3.8}$$

The overall score for a state s is thus calculated as:

$$V^{OW}(s) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} w_k w_{kl} D_{kl}(s) \tag{3.9}$$

The best outcomes achieve the highest weighted sum of dominance.

Optimizer-prioritization scheme

For the optimizer-prioritization scheme, the same pair-wise attribute comparisons are obtained as in equations (3.7) and (3.8) and relative importance of attributes are obtained with equation (3.6) to calculate the overall score for an outcome as follows:

$$V^{OP}(s) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} 2^{r_{kl}} D_{kl}(s) \tag{3.10}$$

Outcomes that dominate other outcomes on the most important attributes are more preferred.

The resulting numbers calculated from (3.3), (3.5), (3.9) or (3.10) are used to establish a preference relation between two or more states. Preferences over states $s_1, s_2 \in S$ for DM i are obtained such that if $V_i(s_1) > V_i(s_2)$, then s_1 is more preferred than s_2 by DM i. Mathematically, $s_1 \succ_i s_2$. Furthermore, if $V_i(s_1) = V_i(s_2)$, then DM i is indifferent between

s_1 and s_2. Mathematically, $s_1 \sim_i s_2$. Note that $V_i(s_1) - V_i(s_2)$ gives no meaningful information about the strength of preference.

Hence, preferences over all states based on a DM's values can be determined by ordering the states according to scores obtained from one of the above relative valuation schemes. These preferences may then serve as input to a GMCR model. For the purposes of this work, an algorithm for scoring states will be integrated into an ABMS platform that utilizes GMCR solution concepts to model decision making behaviour.

3.4 Application to a common pool resources conflict

The proposed methodology for preferences construction is applied in this section to a multiple-participant common-pool resources conflict that is also used in other work (Bristow et al., 2012a, 2013a). Here, the process of constructing preferences and the resulting variability in preferences and conflict dynamics due to different value systems and ordering schemes are demonstrated. Finally, a sensitivity analysis is undertaken to show the sensitivity of a conflict outcome to inputs of the value system model.

3.4.1 Common-pool resources game

There are several different challenges faced by common-pool resources users that can be modeled as games. These challenges include appropriation externality, assignment problems, resource provision, and monitoring (Ostrom et al., 1994). For application of the preferences construction methodology, appropriation externality and monitoring are modeled with the following n-player game. Each participant, uniquely identified by the term DM i, where $i = 1, 2, \ldots, n$, is an appropriator and simultaneously has the authority to monitor and sanction its neighbour in front who is denoted as DM $i + 1$ (note: DM 1 is in front of DM n). To demonstrate the preferences construction methodology and resulting conflict dynamics, a numerical example is provided later in this chapter for a CPR conflict involving 8 DMs. Eight participants are used in order to demonstrate the methodology because Ostrom et al. (1994) have shown that 8 people are sufficient to approximate some characteristics of larger groups or conflict-ridden small groups. The arrangement of the 8 DMs is illustrated in Figure 3.2, in which their strategies and interactions are frozen in a particular state of the conflict

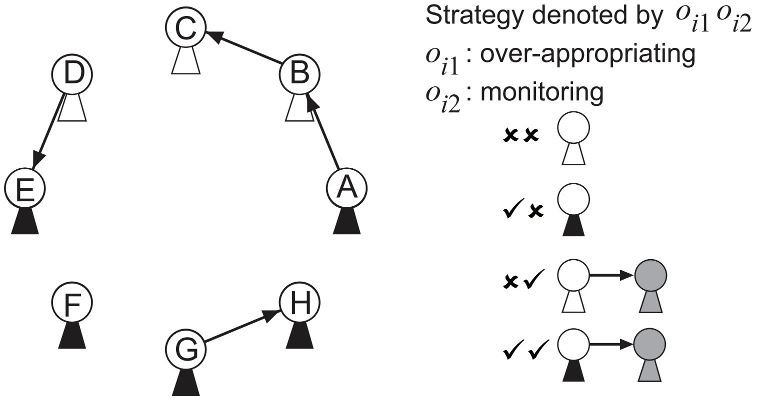


Figure 3.2: Eight agents arranged in an octagon: 5 are over-appropriating, 4 are monitoring and 2 are caught over-appropriating.

model. Hence, there are four strategies from which to choose. A participant can either take a fair share or over-appropriate. At the same time, a participant can either monitor or not monitor his neighbour directly in front of him. The four strategies available to DM i are thus listed in Table 3.1. A "✓" means that the option is selected and an "✗" means that the option is not selected. When the strategies of all n participants are combined, there are in effect 4^n possible states. In the next subsection, a meaningful and efficient process to determine DM i's preferences over all of these states is demonstrated.

Table 3.1: Decision maker's strategies.

Options	**Strategies**			
	1	**2**	**3**	**4**
o_{i1}: Over-appropriate (take more than a fair share)	✗	✗	✓	✓
o_{i2}: Monitor DM $i+1$	✗	✓	✗	✓

3.4.2 Preferences construction

Fundamental objectives

The triple bottom line of sustainability consists of economic, societal and environmental dimensions. In essence, economic, societal and environmental values can be translated into fundamental objectives. The economic objective is to maximize net gains, or conversely, minimize net losses. The societal objective may be to maximize fairness among participants. The environmental objective can be to minimize negative impacts on the environment. Of course, there may be other fundamental objectives; however, for illustration, only these three are included.

Attributes

Attributes to measure the achievement of the above objectives are defined as functions of features of a state and other variables such as rewards (benefits) or penalties (costs). Equations (3.11) to (3.23) are devised by the author. Other variations, of course, on these equations may be used where suitable. In a particular state, a participant may select an option or not. Let $g_{i,j}^{s}(o_{ij})$ represent whether a particular option is taken or not. Therefore,

$$g_{i,j}^{s}(o_{ij}) = \begin{cases} 1 & if\ option\ o_{ij}\ is\ selected\ by\ DM\ i \\ 0 & otherwise \end{cases} \tag{3.11}$$

Hence, $g_{i,1}^{s}$ corresponds to whether DM i takes a fair share or over-appropriates (takes more than a fair share) in state s and $g_{i,2}^{s}$ links to whether DM i monitors or not in state s. The complement of (3.11) is also defined for later use in the attribute functions.

$$\bar{g}_{i,j}^{s}(o_{ij}) = \begin{cases} 0 & if\ option\ o_{ij}\ is\ selected\ by\ DM\ i \\ 1 & otherwise \end{cases} \tag{3.12}$$

Let $n_1^{s,i}$ represent the number of participants, excluding DM i, who take more than a fair share in state s.

$$n_1^{s,i} = \sum_{\iota \in N-i} g_{\iota,1}^{s} \tag{3.13}$$

Let $n_2^{s,i}$ represent the number of participants, excluding DM i, who monitor in state s.

$$n_2^{s,i} = \sum_{\iota \in N-i} g_{\iota,2}^{s} \tag{3.14}$$

Let $n^{s,i}_{1\cap 2}$ represent the number of participants, excluding DM i, who caught an over-appropriating neighbour other than DM i in state s.

$$n^{s,i}_{1\cap 2} = \begin{cases} \displaystyle\sum_{\iota \in N-i-n} g^s_{\iota,2} g^s_{\iota+1,1} \text{ , } if\ i = 1\ or\ n \\ g^s_{n,2} g^s_{1,1} + \displaystyle\sum_{\iota \in N-i-n} g^s_{\iota,2} g^s_{\iota+1,1} \text{ , } otherwise \end{cases} \tag{3.15}$$

For the economic objective, $\mathbb{O}_1$, there are two attributes: 1) B_{11}: the cost-benefit of appropriation, and 2) B_{12}: the cost-benefit of monitoring. The cost-benefit of appropriation, B_{11}, from the perspective of DM *i* takes the value of $b_{11}(s,i)$, which can be calculated using the following equation:

$$b_{11}(s,i) = \begin{cases} \bar{g}^s_{1,1} \dfrac{M}{n}\left(n - n^{s,1}_1\right) + g^s_{1,1}\left(\dfrac{M}{n}\left(n - n^{s,1}_1 - 1\right) + L - g^s_{n,2}F\right) \text{ , } for\ i = 1 \\ \bar{g}^s_{i,1} \dfrac{M}{n}\left(n - n^{s,i}_1\right) + g^s_{i,1}\left(\dfrac{M}{n}\left(n - n^{s,i}_1 - 1\right) + L - g^s_{i-1,2}F\right) \text{ , } otherwise \end{cases} \tag{3.16}$$

where *n* is the number of participants; *M* represents the total benefits that all participants would obtain if everyone took a fair share; L is the additional benefit that one obtains if she over-appropriates by essentially appropriating benefits that would have been distributed to other participants; *F* is a fine that can be imposed by a monitor on an over-appropriator. In order to simulate a dilemma between acting in one's own self-interest and protecting the integrity of the resource, and to dissuade participants from over appropriating, the following conditions are imposed:

$$\frac{M}{n} < L < F \tag{3.17}$$

There is incentive to over-appropriate when the additional benefit that one obtains from over-appropriating is greater than the share that would have been received when everyone takes a fair share. However, there is disincentive to over-appropriate when the fine to be paid for over-appropriating is greater than the additional benefit.

Likewise, the cost-benefit of monitoring, B_{12}, takes the value $b_{12}(s,i)$, which can be calculated with the following equation:

$$b_{12}(s,i) = \begin{cases} \dfrac{F}{n-1} n^{s,n}_{1\cap 2} + g_{n,2}\left(g_{1,1}\left(R + \dfrac{F}{n-1}\right) - E\right) \text{ , } for\ i = n \\ \dfrac{F}{n-1} n^{s,i}_{1\cap 2} + g_{i,2}\left(g_{i+1,1}\left(R + \dfrac{F}{n-1}\right) - E\right) \text{ , } otherwise \end{cases} \tag{3.18}$$

where F is the collected fine equivalent to that imposed in equation (3.16) and is a benefit distributed to all participants except the one who paid the fine; E is the cost to monitor and R is the personal reward given to a monitor who successfully catches an over-appropriator. In order to incentivize participants to monitor, the reward and benefits must be greater than the effort; hence the following condition is imposed:

$$\left(R + \frac{F}{n-1}\right) > E \tag{3.19}$$

For the societal objective, $\mathbb{O}_2$, as for the economic objective, there are two attributes: 1) B_{21}: fairness of appropriation, and 2) B_{22}: justice in catching over-appropriators. Appropriation is socially fair when all participants are taking equal shares, which refers to two extreme cases: either all participants are taking a fair share or all participants are over-appropriating. As more participants gravitate to these norms, the perceived benefits of social cohesion are strengthened. A linear relationship is assumed between perceived benefit and the number of participants taking a fair share or over-appropriating, according to the group with which DM i is associated. A state's score on equal appropriation as perceived by DM i is calculated with the following equation:

$$b_{21}(s,i) = \bar{g}_{i,1}^{s}(n - n_1^{s,i}) + g_{i,1}^{s}(n_1^{s,i} + 1) \tag{3.20}$$

While it may be more desirable to take more than a fair share if the majority does the same, it is still required by justice to penalize over-appropriators. Catching more over-appropriators, even if oneself is an over-appropriator, is thus more appealing. However, it would also be possible to formulate the equation to reflect that a DM prefers not to be caught for over-appropriation. Nonetheless, a state's score on catching over-appropriators is based on the difference between the total number of over-appropriators and the number of over-appropriators who are monitored. With a reference point at unity, each case of over-appropriation decreases a state's score on this attribute while each case of penalized over-appropriation increases it as shown in the following equation:

$$b_{22}(s,i) = \begin{cases} \frac{1}{n}\left(n - \beta(n_1^{s,1} + g_{1,1}^{s}) + n_{1\cap 2}^{s,1} + g_{1,2}^{s}g_{2,1}^{s} + g_{n,2}^{s}g_{1,1}^{s}\right), for\ i = 1 \\ \frac{1}{n}\left(n - \beta(n_1^{s,n} + g_{n,1}^{s}) + n_{1\cap 2}^{s,n} + g_{n,2}^{s}g_{1,1}^{s} + g_{n-1,2}^{s}g_{n,1}^{s}\right), for\ i = n \\ \frac{1}{n}\left(n - \beta(n_1^{s,i} + g_{i,1}^{s}) + n_{1\cap 2}^{s,i} + g_{i,2}^{s}g_{i+1,1}^{s} + g_{i-1,2}^{s}g_{i,1}^{s}\right), otherwise \end{cases} \tag{3.21}$$

Also, to be able to compare all outcomes to one another, this attribute calls into question a value judgment between penalizing appropriation versus avoiding appropriation. A parameter, β, captures this value judgment, where decreasing appropriation by one case is β times better than catching an over-appropriator.

Finally, achievement of the environmental objective, $\mathbb{O}_3$, can be characterized by two attributes: 1) B_{31}: number of participants taking a fair share, and 2) B_{32}: number of participants monitoring. The possible values of these attributes are quite simply expressed as follows:

$$b_{31}(s,i) = n - n_1^{s,i} - g_{i,1}^{s} \tag{3.22}$$

$$b_{32}(s,i) = n_2^{s,i} + g_{i,2}^{s} \tag{3.23}$$

Plots of the attribute functions given in equations (3.16), (3.18), and (3.20) to (3.23) for specified parameters, which take on dummy values listed in Table 3.2, are illustrated in Figure 3.3 (a-f). It can be seen that as the number of over-appropriators increase, a) the benefit-cost of appropriating decreases, as well as measures of d) justice and e) the stewardship of appropriating. Also, if a DM is monitored, a) the benefit-cost of appropriating is less when the DM over-appropriates compared to when the DM takes a fair share. As more participants are monitored and caught for over-appropriating, b) the benefit-cost of monitoring increases as does the measures of d) justice and f) the stewardship of monitoring. The societal attribute of equality of appropriating illustrates a bifurcation where if a DM is part of a majority group then the perception of equality increases, whereas if a DM is part of a minority group then the perception of equality decreases.

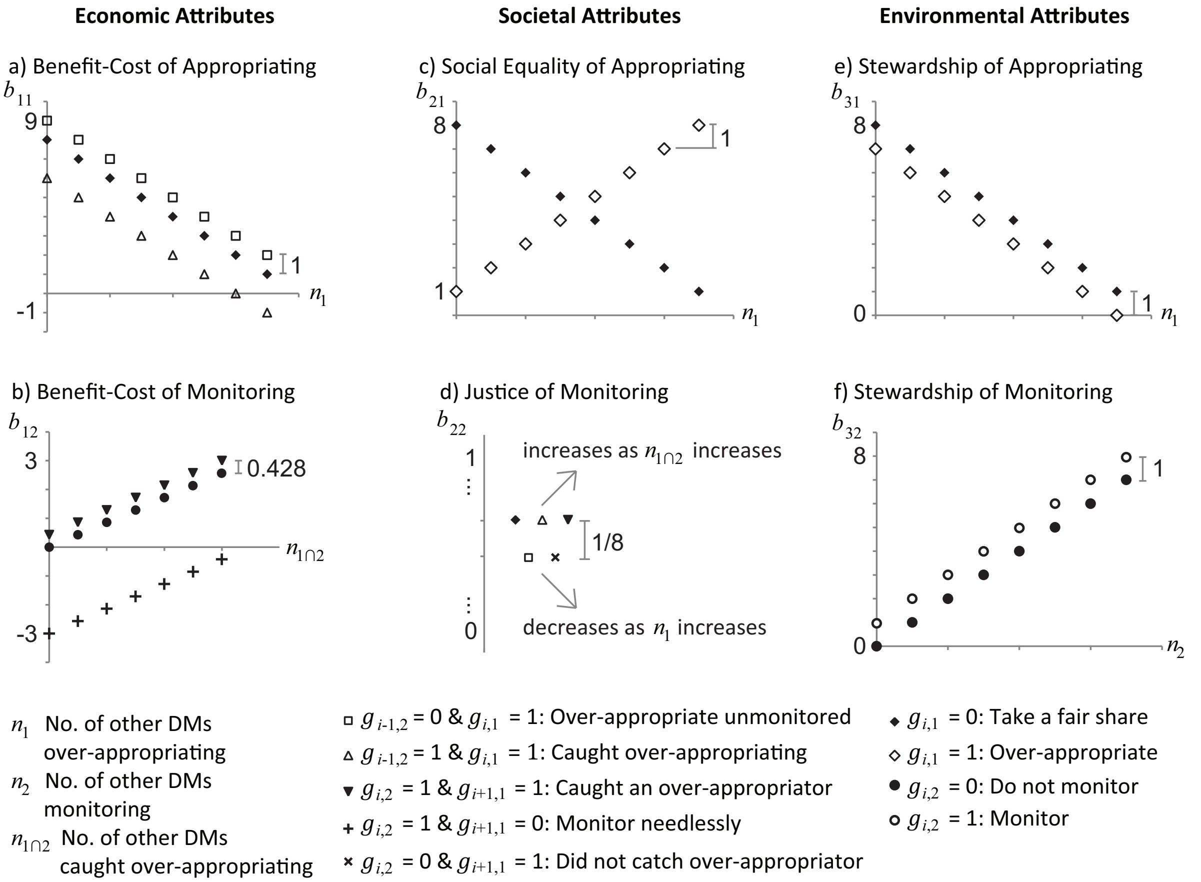


Figure 3.3: States are scored on economic, societal and environmental attributes expressed by functions which are dependent on options selected by participants.

If a participant is a satisficer, then thresholds for all of the attributes need to be specified, whether by value judgments on the part of the participant (for example, 90% achievement in order to be good enough) or by some other systematic method, such as using the average value to distinguish between high and low measurements. Criteria distinguish states that satisfy requirements from those that do not. Setting criteria is a value-laden task. The criteria values are specific to a value system. Essentially, any threshold is valid as long as it reflects the value judgments of the DM. The interpretations of thresholds, used to determine whether a state does or does not meet criteria, are listed in Table 3.3. The mid-values which serve as arbitrary thresholds of the attribute functions in Figure 3.3 (a-f) are listed in the right-most column of Table 3.3.

Table 3.2: Attribute functions' parameters.

Parameter	Description	Constant Value
n	Number of participants	8
M	Total benefits of everyone taking a fair share	8
L	Additional benefit when one takes more than a fair share	2
F	Penalty for over-appropriating	3
E	Cost of monitoring	3
R	Reward for catching an over-appropriator	3
β	One less over-appropriator is β times better than catching an over-appropriator	1

Table 3.3: Interpretation of criteria for appropriation and monitoring attributes.

C_{kl}:Threshold	**Interpretation**	**Mid-Value**
C_{11}	Minimum net gain of benefits from appropriation	4
C_{12}	Minimum net gain of benefits from monitoring	0
C_{21}	Minimum number of like-minded participants	4.5
C_{22}	Minimum fraction of over appropriators monitored	0.5
C_{31}	Minimum number of participants who take a fair share	4
C_{32}	Minimum number of monitors	4

Value system

Fundamental objectives and their corresponding attributes can be organized into a generic value system. Heterogeneity of participants' value systems obtains expression through 1) selection of relevant objectives and attributes, and 2) pair-wise comparisons of relevant objectives and attributes. Table 3.4 is a matrix of the pair-wise comparisons of relevant objectives to be filled in from the perspective of DM i.

Table 3.4: DM i's pair-wise comparison of objectives.

Perspective: DM i	$\mathbb{O}_1$	$\mathbb{O}_2$	$\mathbb{O}_3$		w_k: **Relative Importance**
$\mathbb{O}_1$: Economic objective	1	$r_{\mathbb{O}_1:\mathbb{O}_2}$	$r_{\mathbb{O}_1:\mathbb{O}_3}$	→	w_1
$\mathbb{O}_2$: Societal objective	$\frac{1}{r_{\mathbb{O}_1:\mathbb{O}_2}}$	1	$r_{\mathbb{O}_2:\mathbb{O}_3}$	→	w_2
$\mathbb{O}_3$: Environmental objective	$\frac{1}{r_{\mathbb{O}_1:\mathbb{O}_3}}$	$\frac{1}{r_{\mathbb{O}_2:\mathbb{O}_3}}$	1	→	w_3

If an objective is deemed to be irrelevant by DM i's value system, then the corresponding column and row are omitted.

When making pair-wise comparisons, a DM should be given contextual information (Hobbs and Meier, 2000). For ordinal preferences, contextual information includes the quantization of an attribute, that is, the minimum amount required to indicate a difference between states, the range of measurement, and the criteria threshold. The smallest unit of each attribute, Δb_{kl}, and range, as per the parameters in Table 3.3, are provided in Figure 3.4, which illustrates with arrows the pair-wise comparisons to be made by a DM. The range of an attribute is expressed as $[b_{min}, b_{max}]$ where b_{min} is the minimum and b_{max} is the maximum that can be attained. These values can be obtained for the numerical value from the plots of attribute functions in Figure 3.3. For example, the minimum value of the attribute of benefit-cost of appropriation, b_{11}, is -1, which occurs when all DMs over-appropriate, and the maximum is 9, which is attained when all DMs take a fair share. Hence, the range of the benefit-cost of appropriation for the given numerical example is [-1,9]. Similarly, [-3,3] is the range of the benefit-cost of monitoring; the minimum is attained when one is monitoring while no other DM is over-appropriating and the maximum is reached when one is monitoring when all other DMs are over-appropriating. Other ranges are obtained in a similar manner.

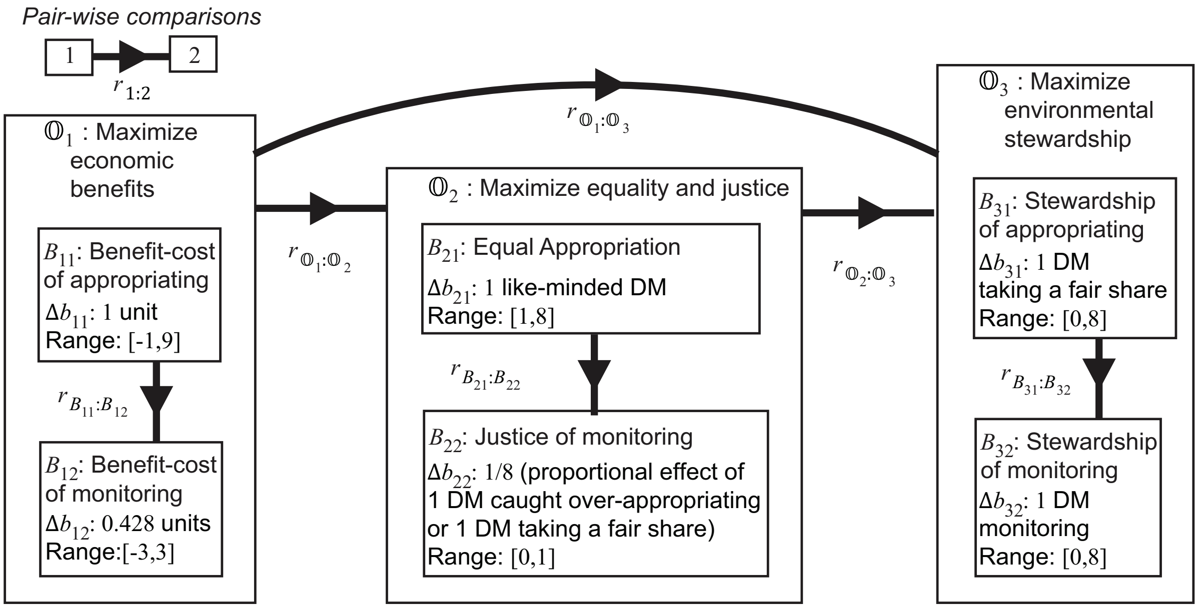


Figure 3.4: Pair-wise comparisons of objectives and attributes to delineate a value system model in which relative importance of objectives and attributes are obtained through AHP (Saaty, 1980).

The relative importance of fundamental objectives is calculated for DM i from the pair-wise comparisons of objectives. For satisficers, it should be understood by the DM that a pair-wise comparison of objectives expresses a value judgment on how much the achievement of one objective is worth compared to achievement of another. Similarly, a pair-wise comparison of attributes should express how much it is worth to meet the criterion on one attribute compared to criterion on another attribute with respect to the achievement of the associated objective. For optimizers, a pair-wise comparison of objectives (attributes) indicates how much an improvement on one objective (attribute) is worth compared to an improvement on another.

Let $r_{\mathbb{O}_1:\mathbb{O}_2}$ represent the pair-wise comparison between objectives $\mathbb{O}_1$ and $\mathbb{O}_2$ with respect to DM i's purpose or mission, where achieving objective $\mathbb{O}_1$ is $r_{\mathbb{O}_1:\mathbb{O}_2}$ times more important than achieving objective $\mathbb{O}_2$. For example, achieving the economic objective is $r_{\mathbb{O}_1:\mathbb{O}_2}$ times more important than achieving the societal objective, or conversely, achievement of the societal objective is worth $1/r_{\mathbb{O}_1:\mathbb{O}_2}$ times achievement of the economic objective. Note that $r_{\mathbb{O}_1:\mathbb{O}_1}$ equals one. After pair-wise comparisons are completed, the normalized eigenvalues of the matrix express the relative importance of the corresponding objectives. Of course, the normalized eigenvalues may be quickly estimated by multiplying the elements in each row, then taking the Kth root where K is the number of objectives, and finally, normalizing the resulting numbers (Saaty, 1980). Mathematically, the relative importance of the kth objective is calculated as follows:

$$\mathcal{w}_k = \left[\left(\prod_{\gamma=1}^{k} \frac{1}{r_{\mathbb{O}_\gamma:\mathbb{O}_k}}\right)\left(\prod_{\delta=k}^{K} r_{\mathbb{O}_k:\mathbb{O}_\delta}\right)\right]^{1/K} \tag{3.24}$$

$$w_k = \frac{\mathcal{w}_k}{\sum_{\varepsilon=1}^{K} \mathcal{w}_\varepsilon} \tag{3.25}$$

Table 3.5 is a matrix of the pair-wise comparisons of relevant attributes with respect to the achievement of objective $\mathbb{O}_k$. The term $r_{B_{k1}:B_{k2}}$ represents how much attribute B_{k1} contributes to the achievement of objective $\mathbb{O}_k$ compared to attribute B_{k2}; that is, attribute B_{k1} contributes $r_{B_{k1}:B_{k2}}$ times more or less toward the achievement of objective $\mathbb{O}_k$ than attribute B_{k2}, or conversely, attribute B_{k2} contributes $1/r_{B_{k1}:B_{k2}}$ times more or less toward the achievement of objective $\mathbb{O}_k$ than attribute B_{k1}. Similarly, $r_{B_{k1}:B_{k1}}$ is equal to one.

Table 3.5: DM i's pair-wise comparison of appropriation and monitoring attributes with respect to the achievement of the kth objective.

Perspective: DM i, $\mathbb{O}_k$	B_{k1}	B_{k2}		w_{kl}: **Relative Contribution**
B_{k1}: appropriation attribute	1	$r_{B_{k1}:B_{k2}}$	→	w_{k1}
B_{k2}: monitoring attribute	$\frac{1}{r_{B_{k1}:B_{k2}}}$	1	→	w_{k2}

The relative importance of the lth attribute to the achievement of the kth objective, w_{kl}, is calculated as follows:

$$\mathcal{w}_{kl} = \left[\left(\prod_{\gamma=1}^{l} \frac{1}{r_{B_{k\gamma}:B_{kl}}}\right)\left(\prod_{\delta=l}^{L_k} r_{B_{kl}:B_{k\delta}}\right)\right]^{1/L_k} \tag{3.26}$$

$$w_{kl} = \frac{\mathcal{w}_{kl}}{\sum_{\varepsilon=1}^{L_k} \mathcal{w}_{k\varepsilon}} \tag{3.27}$$

where L_k is the number of attributes associated with the kth objective.

Archetypal value systems which represent polarized perspectives are listed in Table 3.6. An economic-focused value system is represented by value judgments in which the economic objective is nine times more important than the societal and environmental objectives, which are equal. Likewise, a societal-focused value system is delineated by judgments in which the societal objective is nine times more important than the other two, while the others are equal. Finally, an environmental-focused value system assigns the environmental objective as nine times more important than any other objective; other objectives are equal. For all three value systems, the attributes for each objective are judged to be equal. Note that these value systems represent polarized perspectives rather than extremes because the other objectives are still taken into account, whereas in an extreme value system, objectives other than the ultimate objective would be irrelevant and thus omitted.

Table 3.6: Archetypal value systems.

	$r_{\mathbb{O}_1:\mathbb{O}_2}$	$r_{\mathbb{O}_1:\mathbb{O}_3}$	$r_{\mathbb{O}_2:\mathbb{O}_3}$	$r_{B_{11}:B_{12}}$	$r_{B_{21}:B_{22}}$	$r_{B_{31}:B_{32}}$	$w_1 w_{11}$	$w_1 w_{12}$	$w_2 w_{21}$	$w_2 w_{22}$	$w_3 w_{31}$	$w_3 w_{32}$
ECON	9	9	1	1	1	1	0.41	0.41	0.045	0.045	0.045	0.045
SOC	1/9	1	9	1	1	1	0.045	0.045	0.41	0.41	0.045	0.045
ENV	1	1/9	1/9	1	1	1	0.045	0.045	0.045	0.045	0.41	0.41

Ordinal preferences

Finally, ordinal preferences are obtained by invoking one of the four comparison-aggregation schemes detailed in subsection 3.3.3. To demonstrate how the different comparison-aggregation schemes impact ordinal preferences, consider the following examples in which a DM compares a status quo state to future states to which she can move unilaterally. In the first example, the status quo state is assumed to be the state in which the particular DM is currently taking more than a fair share and monitoring. Looking to her neighbours, she sees that the one in front is taking a fair share and the one behind is monitoring. Also, the number of other DMs who are taking more than a fair share is low. Likewise, the number of other DMs who are monitoring is also low. Consequently, not many DMs are caught taking more than a fair share. In Table 3.7, the first column lists the available strategies for the particular DM. She can stay with her current strategy (4: ✓✓) or change to one of three other strategies (1: ✗✗, 2: ✗✓, 3: ✓✗).

Table 3.7: Calculations of satisficer and optimizer weighting schemes for archetypal value systems.

status quo: $g_{i-1,2}^{s} = 1;\ g_{i+1,1}^{s} = 0;\ n_1^{s,i} < \frac{n}{2};\ n_2^{s,i} < \frac{n}{2};\ n_{1\cap 2}^{s,i} < \frac{n}{2}$

a) Satisficer

Strategy: $o_{i1}o_{i2}$	Comparisons to criteria thresholds						V^{SW}		
	c_{11}	c_{12}	c_{21}	c_{22}	c_{31}	c_{32}	ECON	SOC	ENV
4: ✓✓ (status quo)	0	0	0	1	1	0	0.090	0.455	0.455
1: ✗✗	1	1	1	1	1	0	0.955	0.955	0.590
2: ✗✓	1	0	1	1	1	0	0.545	0.910	0.545
3: ✓✗	0	1	0	1	1	0	0.500	0.500	0.500

b) Optimizer

Strategy: $o_{i1}o_{i2}$	Comparisons to status quo state						V^{OW}		
	d_{11}	d_{12}	d_{21}	d_{22}	d_{31}	d_{32}	ECON	SOC	ENV
4: ✓✓ (status quo)	0	0	0	0	0	0	0	0	0
1: ✗✗	+1	+1	+1	0	+1	-1	+0.865	+0.500	+0.135
2: ✗✓	+1	0	+1	0	+1	0	+0.500	+0.500	+0.500
3: ✓✗	0	+1	0	0	0	-1	+0.365	0	-0.365

If the particular DM is a satisficer, then the attributes of each state are compared to criteria. Columns 2-7 of Table 3.7a) provide the results of the comparisons where “0” signifies that the criterion is not met and “1” means that the criterion is met. Columns 8-10 of the same table are calculated using equation (3.3). In this particular case, there are only effective differences among the status quo and the other states with respect to the economic attributes and the societal attribute of equal appropriation. The cost-benefit of appropriation changes from being unacceptable to acceptable for the particular DM if she changes her strategy from taking more than a fair share to taking a fair share. The fairness of appropriation also becomes acceptable as she joins the majority of other participants who are taking a fair share. Furthermore, since her neighbour in front is taking a fair share, the cost-benefit of monitoring would be acceptable if she stopped monitoring. No difference is observed for the societal attribute of penalized over-appropriation because there is no loss in that attribute from any change in her strategy. Finally, there is no difference in the environmental attributes because there is not enough loss, or gain, to effect a dip below a threshold, or meeting of a criterion. As a result, ECON, SOC and ENV value systems all suggest that the states in which the DM selects strategies 1, 2, or 3 are more preferred than the status quo and in particular, strategy 1, in which the DM takes a fair share and does not monitor, should be selected from among them.

On the other hand, if the particular DM is an optimizer, then the future states are compared to the status quo. Columns 2-7 of Table 3.7b) provide the results of the comparisons where “-1” indicates that the future state is worse than the status quo; “0” signifies that the future state is equal; and “+1” means that the future state is better. Columns 8-10 of the same table are calculated using equation (3.9). In this case, the environmental attributes are affected. By taking a fair share, the stewardship of appropriation increases. By not monitoring, the stewardship of monitoring decreases. In effect, the difference between satisficing and optimizing schemes can be seen in comparing the last rows of Tables 3.7 a) and b), in the evaluation of strategy 3 (✓✗) compared to the status quo (✓✓). For a satisficer, the state containing strategy 3 is more preferred than that status quo by ECON, SOC and ENV value systems. For an optimizer, the state in which strategy 3 is selected is still more preferred than the status quo by ECON, but equally preferred by SOC, and furthermore, less preferred by ENV. If strategy 3 were the only alternative, then a DM would make a different decision based on which value system she used to evaluate the decision.

In the next example, a DM is characterized by a distinct value system for which pair-wise comparisons of objectives and attributes are given in the second row of Table 3.8. Relative importance of objectives and attributes are obtained through AHP and the weights used in the weighting scheme are recorded in Table 3.8, along with the priorities used in the prioritization scheme. According to this distinct value system, the benefit-cost of appropriation is the most important attribute followed in order by the fairness of appropriation, the stewardship of appropriation, the justice attribute, the benefit-cost of monitoring, and finally, the stewardship of monitoring.

Consider a different status quo state in which a DM is currently taking a fair share and not monitoring. Looking to her neighbours, she sees that the one in front is also taking a fair share and the one behind is likewise not monitoring. Also, the number of other DMs who are taking more than a fair share is low. In the first column of Table 3.9, her current strategy is 1: ×× and the available strategies are: 2: ×✓, 3: ✓×, 4: ✓✓. This example demonstrates the difference between weighting and prioritization schemes for a distinct value system. The weighting scheme numbers in column 9, calculated from equation (3.9), suggest that compared to the status quo, future states are less preferred. Despite a gain in the cost-benefit of appropriation when a DM over-appropriates, it is not enough to compensate for the accompanied loss in fairness, justice, and environmental stewardship. Therefore, the particular DM would not change her strategy. If the DM would rather prioritize attributes than consider the tradeoffs among them, however, then according to the numbers in column 10 which were obtained with equation (3.10), the DM would change her strategy from taking a fair share to taking more without regard for the societal and environmental impacts.

Table 3.8: A distinct value system for which weighting and prioritization schemes render different preferences.

	$r_{\mathbb{O}_1:\mathbb{O}_2}$	$r_{\mathbb{O}_1:\mathbb{O}_3}$	$r_{\mathbb{O}_2:\mathbb{O}_3}$	$r_{B_{11}:B_{12}}$	$r_{B_{21}:B_{22}}$	$r_{B_{31}:B_{32}}$
Distinct Comparisons	1.20	1.50	1.25	3	2	4
↓						
Weighting Scheme (WEIGHTED)	w_1w_{11}	w_1w_{12}	w_2w_{21}	w_2w_{22}	w_3w_{31}	w_3w_{32}
	0.300	0.100	0.222	0.111	0.213	0.053
Prioritization Scheme (PRIORITIZED)	p_{11}	p_{12}	p_{21}	p_{22}	p_{31}	p_{32}
	6	2	5	3	4	1

Table 3.9: Calculations of optimizer weighting and prioritization schemes for a distinct value system

status quo: $g^s_{i-1,2} = 0;\ g^s_{i+1,1} = 0;\ n^{s,i}_1 < \frac{n}{2};\ n^{s,i}_2 < \frac{n}{2};\ n^{s,i}_{1\cap 2} < \frac{n}{2}$

Strategy: $\boldsymbol{o_{i1}o_{i2}}$	d_{11}	d_{12}	d_{21}	d_{22}	d_{31}	d_{32}		V^{OW}: Weighted	V^{OP}: Prioritized
1: ×× (status quo)	0	0	0	0	0	0	→	0	0
2: ×✓	0	-1	0	0	0	+1	→	-0.047	-2
3: ✓×	+1	0	-1	-1	-1	0	→	-0.247	8
4: ✓✓	+1	-1	-1	-1	-1	+1	→	-0.293	6

It is important for the particular DM to validate the preferences obtained from the value system model against actual preferences. This can be done by presenting a DM with cases such as those presented in the above examples and asking whether the suggested preferences align with her actual preferences. Moreover, if historical data for a particular conflict is available, the modeled preferences may be inputted into a GMCR model and equilibrium states may be compared with actual resolutions to determine validity of the value system models for participants in the conflict.

3.4.3 Conflict dynamics

Using the ordinal preferences obtained from archetypal value systems, the conflict dynamics of the appropriation-monitoring CPR game are simulated using the agent-based framework introduced by Bristow et al. (2013a). In the simulated environment, there are eight DMs. To isolate the effects of different value systems and comparison-aggregation schemes on conflict dynamics, all agents employ a Nash decision rule (Nash, 1950, 1951; Fang et al., 1993; Bristow et al., 2013a) to select their strategy in the next time step. Essentially, a DM evaluates the current state and future states that are unilaterally reachable by a change in her strategy. If all future states are equally or less preferred than the current state, then the current state is Nash stable for the particular DM and she does not change her strategy. On the other hand, if at least one future state is more preferred than the current state, then the current state is Nash unstable and she will change her strategy. If there is greater than one more preferred future state, then she selects the strategy that would lead to the highest ranking state. The desired outcome of this particular game is the cooperative state of all DMs taking a fair share. Simulation results of the 8-participant CPR conflict for the archetypal value systems are plotted in Figures 3.5 to 3.9.

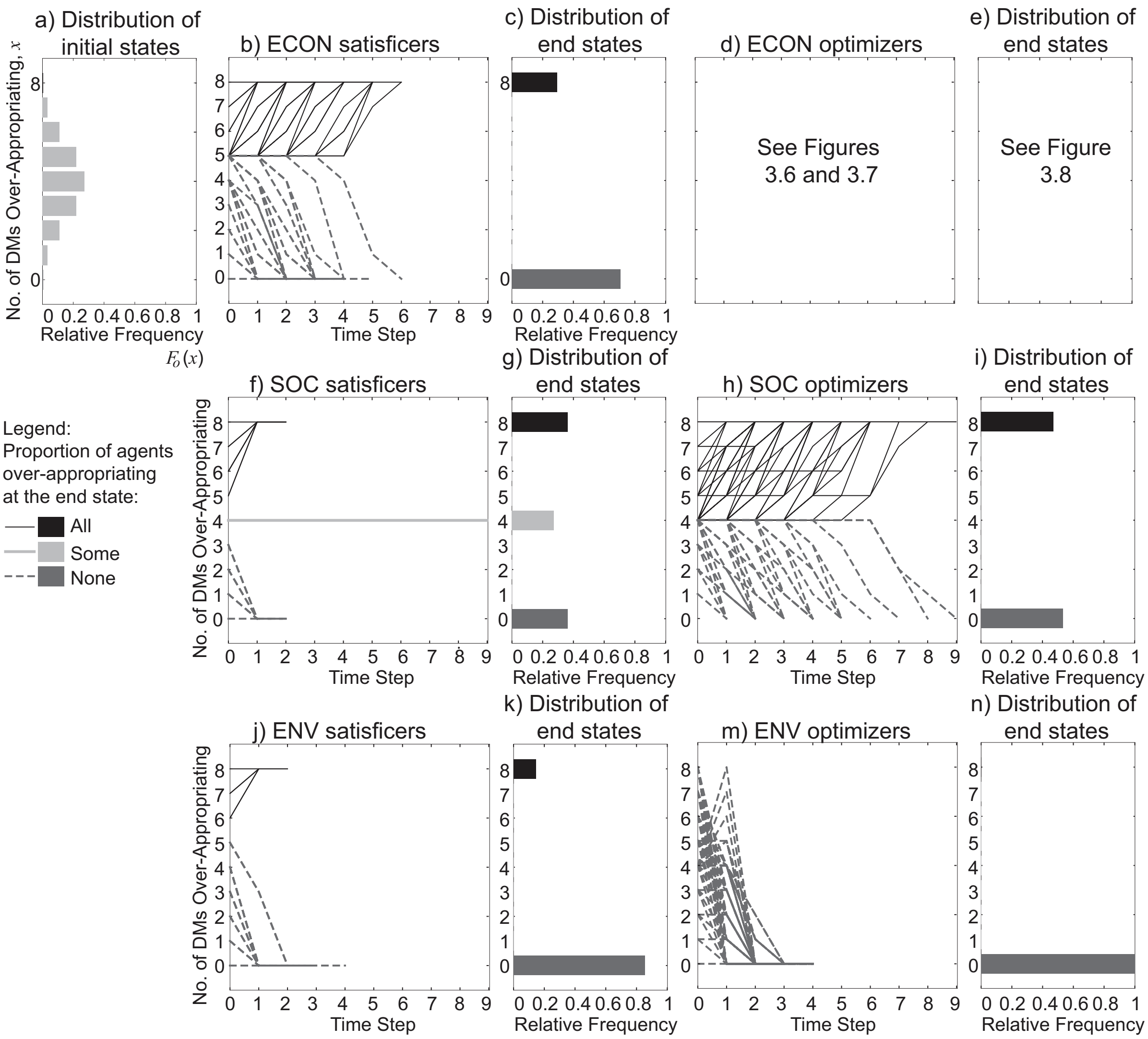


Figure 3.5: Comparisons of the effects of ECON, SOC and ENV value systems and of satisficing versus optimizing value schemes on the number of over-appropriators over time and the distribution of end states.

Figure 3.5a shows the distribution of all initial states, $n_s = 65{,}536$, over the possible scenarios of the number of agents over-appropriating (participants taking more than a fair share). It is essentially a binomial distribution. The distribution can be expressed as the set of binomial coefficients normalized by the sum of all the coefficients:

$$a_x = \binom{8}{x}, x = 0,1,2,\ldots,8 \tag{3.28}$$

$$F_o(x) = \frac{a_x}{\sum a_x} \tag{3.29}$$

If all states are equally probable to be the initial state, then $F_o(x)$ is the relative frequency where x agents are over-appropriating at the start of a simulation.

Figure 3.5b plots the change in the number of over-appropriators over time for all unstable initial states as determined by participants with an ECON value system who are satisfied by average performances on attributes. In general, only states in which all or zero participants take a fair share are stable for all participants. All other states evolve to one of these two extremes. Specifically, 29.4% of all initial states end in all DMs over-appropriating, while 70.6% end in all DMs taking a fair share, as illustrated in Figure 3.5c.

Similarly, in Figure 3.5f, participants with a SOC value system who are also satisfied by average performances on attributes find, in general, that states in which all or zero DMs take a fair share are stable. States in which four DMs over-appropriate and four others take a fair share are unstable because all DMs can unilaterally improve their standing by joining the other group. The cumulative effect of all DMs' decisions, however, maintains the status quo of four DMs over-appropriating and four other DMs taking a fair share. This case illustrates the concept of a dynamic equilibrium; on the micro-level of individual behaviour, the local state is always in flux, while on the macro-level of group behaviour, the global state is essentially unchanged. Overall, the distribution of end states is thus 36.3% of states with all DMs over-appropriating, 27.3% with half over-appropriating and half taking a fair share, and finally, 36.3% with all DMs taking a fair share, as shown in Figure 3.5g.

In the case of an ENV value system for all DMs and satisficing to average performances on attributes, the two extremes of all or zero participants taking a fair share are the only stable end states. As can be seen in Figure 3.5j, if six or more are over-appropriating, then all DMs will end up over-appropriating, whereas if five or fewer over-appropriate, then all DMs will end up taking a fair share. This division results in 14.5% of end states with all DMs over-appropriating and 85.5% with all DMs taking a fair share, as depicted in Figure 3.5k.

On the right-hand side of Figure 3.5, simulation results from optimizing value schemes are plotted for comparison to satisficing value schemes. The collective behaviour of participants who optimize with an ECON value system results in never ending cycles, which are plotted in detail in Figures 3.6 and 3.7. The distribution of end states is presented in Figure 3.8. The results of optimizing ECON DMs will be discussed later. In Figure 3.5h, societal-focused optimizers go through more varied paths towards the two extreme end states of appropriation compared to societal-focused satisficers. There is no dynamic equilibrium of half of DMs over-appropriating and half taking a fair share. Instead, 46.9% of end states involve all DMs over-appropriating and 53.1% comprise all DMs taking a fair share, as shown in Figure 3.5i. Moreover, environmental-focused optimizers are the only group that will converge to all participants taking a fair share from all initial states. In Figure 3.5m, there is temporal instability in which the number of participants who over-appropriate will increase and even reach the maximum. However, the DMs' intrinsic valuation of environmental stewardship over economic costs eventually brings over-appropriation down to zero in time.

In general, equilibrium states which are "stable fixed points" exist in the above simulations. That is, after a finite amount of time DMs will stay at their current strategy. An unexpected exception was encountered in the group of societal-focused satisficers in which four DMs were initially taking a fair share and the other four DMs were over-appropriating. While the number of DMs over-appropriating never changed, DMs were constantly changing their strategy in response to their neighbours' appropriation and monitoring behaviour. In this case, no stable fixed point state is reached. Due to the parameter values in calculating the cost-benefit of appropriation and the cost-benefit of monitoring, there is an incentive to monitor when a neighbour is over-appropriating and to over-appropriate when a neighbour is not monitoring. Conversely, it is better to not monitor when a neighbour is taking a fair share and to take a fair share when a neighbour is monitoring. As a result, DMs may exhibit a pattern of flip-flopping behaviour when they implement pure strategy, that is, a strategy that is deterministic.

Moreover, the state of the conflict is ever-changing with respect to optimizing economic-focused participants. There are no stable fixed point states when all participants optimize with ECON value systems. Eventually, a limit cycle is encountered, which is a type of dynamic equilibrium in which certain states repeat periodically. Figure 3.6 shows three examples of conflict evolution from different initial states. In the first column of the figure is a plot of the number of over-appropriators (x) over time (t) and in the second column is a phase plot in which the change in the number of over-appropriators, $\Delta x = x(t+1) - x(t)$, is on the vertical axis and the number of over-appropriators, $x(t)$, is on the horizontal axis. The first row is a simulation with a transient period of state changes followed by a pattern of cyclic state changes. The number of over-appropriators varies from four to seven in a loop that can be easily seen in the phase space. The second row shows a simulation in which the initial state is already within a limit cycle; hence there is no transient period. Finally, the last row is an example in which the group settles in a dynamic equilibrium in which the number of over-appropriators is unchanging despite changes in the local states of DMs.

Figure 3.7 displays all the other possible dynamic equilibria that can be encountered. The time periods range from two to six time steps. Fifteen unique limits cycles and two dynamic equilibria in which the number of over-appropriators is unchanging despite changes in the local states of DMs were observed.

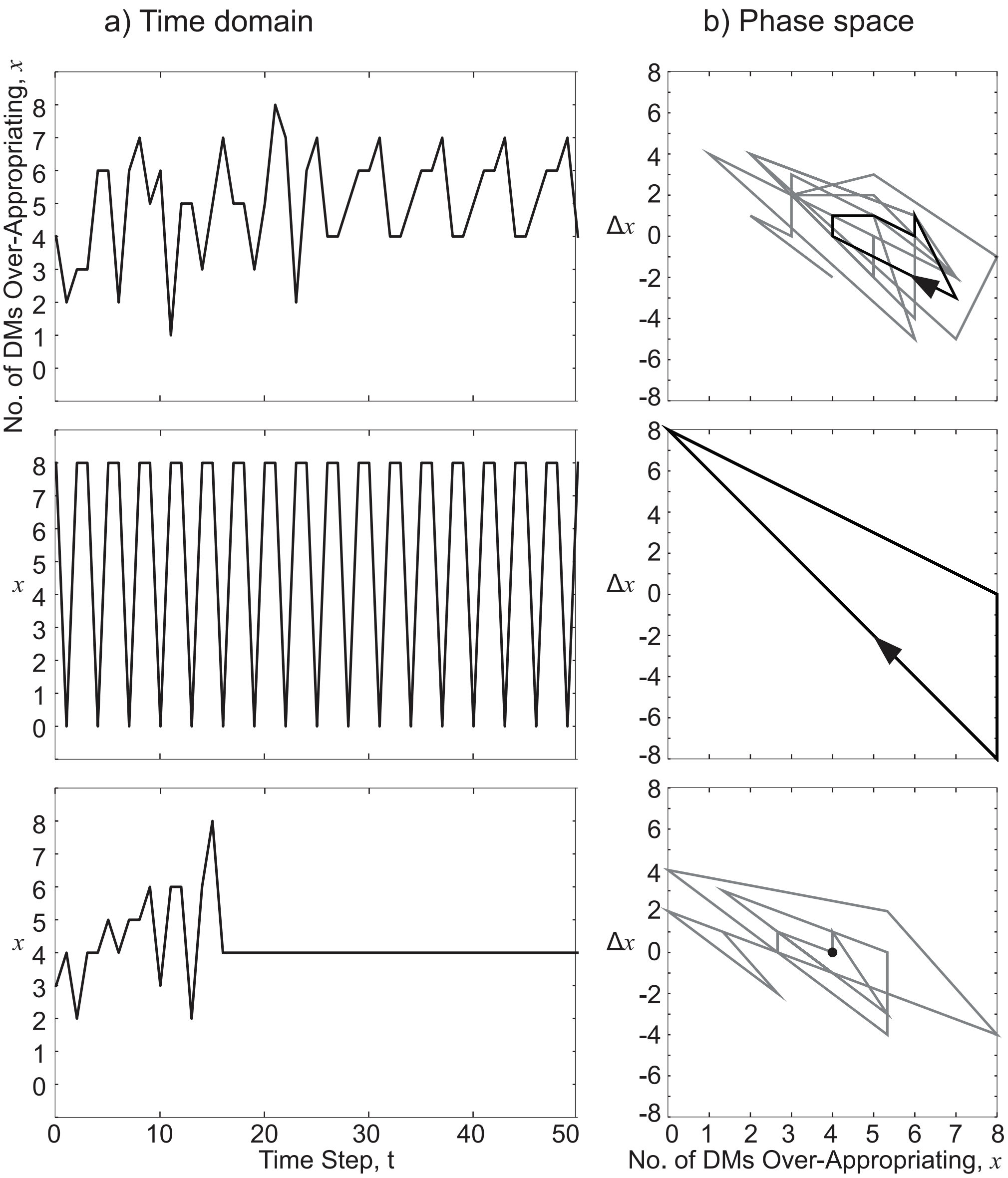


Figure 3.6: Examples of conflict evolutions a) over time and b) in a phase space resulting from strategic interactions among DMs who employ an ECON value system and optimizing value scheme.

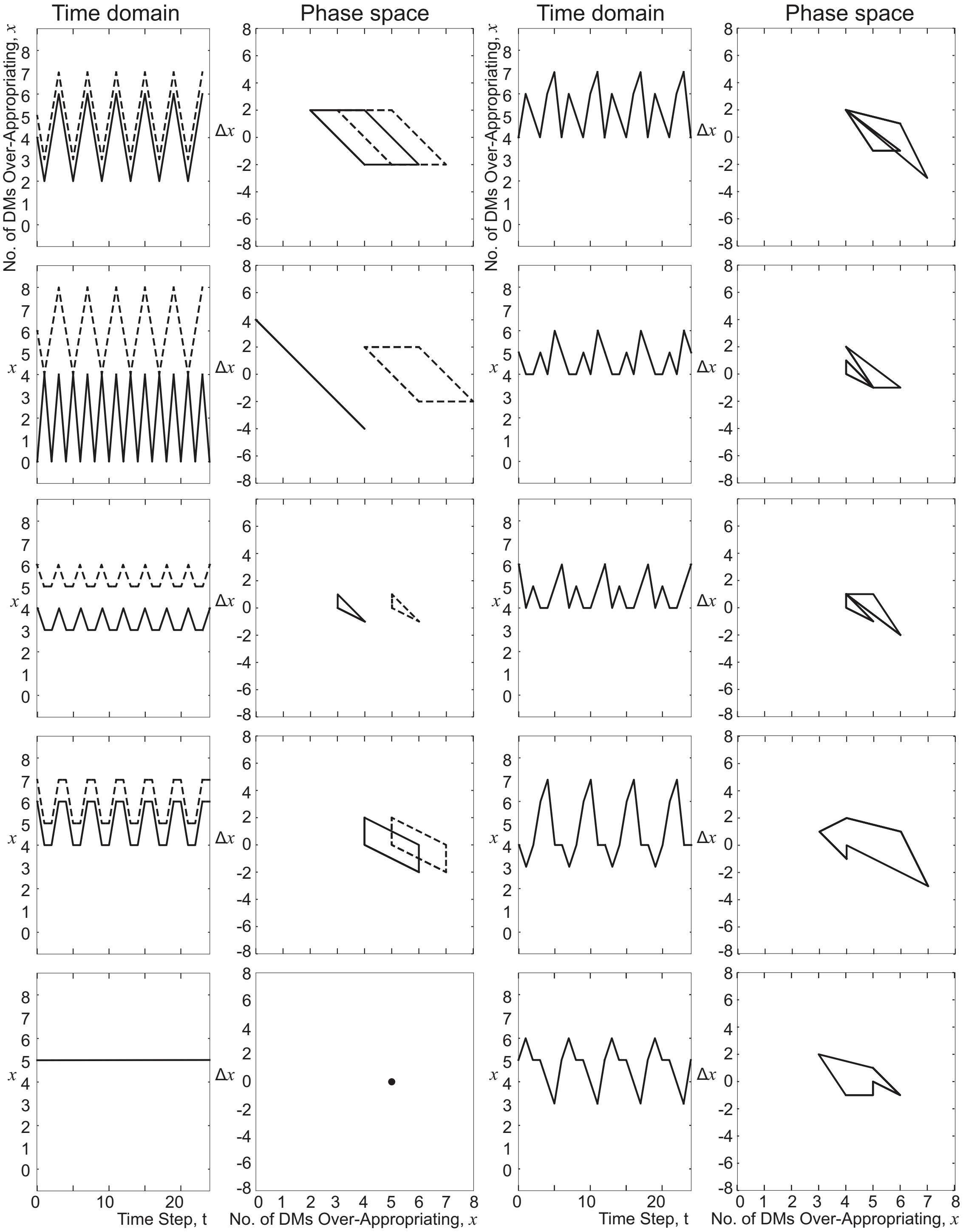


Figure 3.7: Limit cycles and a dynamic equilibrium encountered by optimizing economic-focused DMs in the CPR appropriation and monitoring game.

In order to calculate the distribution of end states, the contribution of a particular state in a limit cycle is proportionate to its frequency in the limit cycle. For example, a limit cycle that repeated the following pattern of [0,8,8] would contribute 1/3 to the bin of zero DMs over-appropriating and 2/3 to the bin of eight DMs over-appropriating. A comparison of the distribution of initial states to the distribution of end states for the simulations of optimizing economic-focused DMs is provided in Figure 3.8. As can be seen in the figure, the distribution of end states is skewed to the upper range of numbers of over-appropriation with half over-appropriating and half taking a fair share for 39.3% of the time. The relative frequency of zero over-appropriation is 0.1% and of all over-appropriating is 0.6%. In contrast to all of the other cases thus far, when all DMs are optimizing and economic-focused the emergent behaviour of the group is mixed rather than extreme.

As a final comparison of different preferences on conflict dynamics, consider the distinct value system specified in Table 3.8 and the effects of using a prioritization scheme versus a weighting scheme to obtain preferences. Figure 3.9 illustrates the results. In these simulations, all DMs are optimizers. When all DMs use the prioritization scheme, no equilibrium states exist. Instead, DMs encountered cyclic end states, which are overlapped in Figure 3.9b and for which the limit cycles are plotted in a phase space in Figure 3.9c. In fact, the distribution of these end states is similar to the distribution of initial states, as shown in

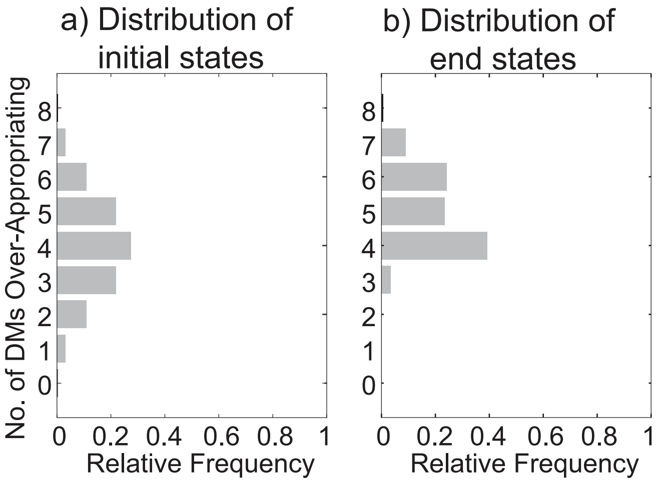


Figure 3.8: Comparison of the distribution of initial states and the distribution of end states in limit cycles encountered by optimizing DMs with an economic-focused value system.

Figure 3.9d. Recall that with a prioritization scheme, the economic attributes were of highest priority for the distinct value system. On the other hand, when all DMs employ the weighting scheme, 98.2% of all simulations end with all DMs taking a fair share. It requires twelve or fewer time steps to reach an equilibrium state, as shown in Figure 3.9e. For the remaining 1.8% of simulations, DMs are caught in a limit cycle or dynamic equilibrium. The dynamic equilibria in which the number of over-appropriators is unchanging are four and five over-appropriators. One limit cycle is three time steps long and flip-flops between five and six over-appropriators. The other limit cycle alternates between five and seven over-appropriators over four time steps.

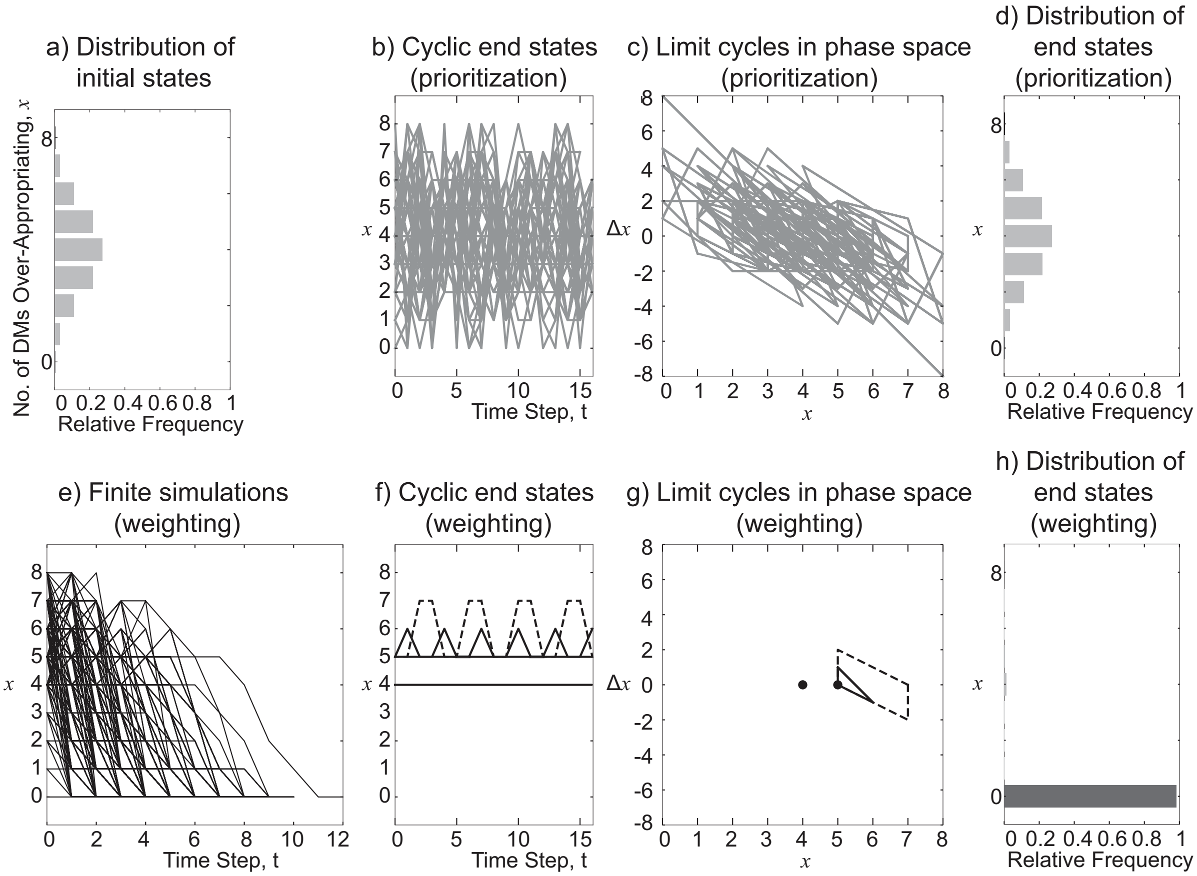


Figure 3.9: Comparison of the effects of prioritization versus weighting schemes, given a distinct value system.

The simulation results can be interpreted to indicate the effectiveness of certain rules. It can be seen that for this particular arrangement of monitoring one's neighbour, the desired cooperative outcome of zero over-appropriation is reachable under certain conditions for certain groups differentiated by their value system and other factors that determine their preferences. However, only for two groups does the desired outcome prevail despite initial conditions. Specifically, environmental-focused optimizers always reach zero over-appropriation and optimizing DMs with the distinct value system specified in Table 3.8, who employ a weighting scheme, reach zero over-appropriation from 98.2% of all initial states. Hence, it is possible to develop an understanding of which rules align well with which value systems.

The impacts of the value judgments, comparison methods and aggregation schemes to obtain preferences from values are significant in terms of the effects on individual decisions of a DM and strategic interactions among a group of DMs. It is not at first obvious how the various factors in obtaining preferences will influence the conflict dynamics among participants. Upon analysis of the simulation results, however, generalizations become apparent. For example, a group containing DMs who seek to optimize rather than satisfice experience greater volatility in the interactions with their neighbours. Satisficers tend to reach equilibrium states and do so in less time steps due to the inertia in changing one's strategy unless a significant improvement is expected from passing a threshold. The outcome of this particular appropriation and monitoring game can be vastly different depending on whether preferences are obtained using a prioritization or weighting scheme. In these cases it is important to understand the implications of how DMs determine their preferences in order to effectively design rules or policies to govern CPR.

3.4.4 Sensitivity analysis

A sample case sensitivity analysis is used to demonstrate how much the conflict dynamics would be affected under various degrees of perturbation in the inputs that are used to determine a DM's value system. The particular inputs that are perturbed are the pair-wise comparisons of objectives, $r_{\mathbb{O}_1:\mathbb{O}_2}$, $r_{\mathbb{O}_1:\mathbb{O}_3}$, $r_{\mathbb{O}_2:\mathbb{O}_3}$, and pair-wise comparisons of their respective attributes, $r_{B_{11}:B_{12}}$, $r_{B_{21}:B_{22}}$, $r_{B_{31}:B_{32}}$, which are collected via Tables 3.4 and 3.5.

These inputs are varied with a uniform probability distribution, such that the width of the uniform probability distribution is proportionate by some degree of variability to the magnitude of the given input value. A random variable with a uniform probability distribution is defined as follows.

$$\tilde{u} \sim U(-k_{degree}v, k_{degree}v) \tag{3.30}$$

where $\tilde{u}$ is a random variable specifying the amount of perturbation, v is the given input value, k_{degree} is the degree of variability, and U is a uniform distribution centered about zero with upper and lower bounds that are proportionate to the given input value by the degree of variability. Hence, a perturbed input is obtained with the following operation.

$$\tilde{v} \sim v + \tilde{u} \tag{3.31}$$

where $\tilde{v}$ is a random variable specifying possible values of a perturbed input. The range of each value system input is provided as an example in Table 3.10 for 10% variability of the ECON value system.

Table 3.10: Range of perturbed value system inputs with 10% variability.

	$r_{\mathbb{O}_1:\mathbb{O}_2}$	$r_{\mathbb{O}_1:\mathbb{O}_3}$	$r_{\mathbb{O}_2:\mathbb{O}_3}$	$r_{B_{11}:B_{12}}$	$r_{B_{21}:B_{22}}$	$r_{B_{31}:B_{32}}$
Nominal value	9	9	1	1	1	1
Upper bound	9.9	9.9	1.1	1.1	1.1	1.1
Lower bound	8.1	8.1	0.9	0.9	0.9	0.9

As a case for analysis, the initial state is fixed at state 64853 in which seven DMs are over-appropriating, three are monitoring and two are caught. The inputs for the ECON value system are used. State 64853 was chosen as the initial state because different outcomes were observed for several simulation runs of satisficing DMs with the ECON value system. In particular, the simulation could evolve to an end state in which either all DMs over-appropriate or all take a fair share. Figure 3.10a shows the conflict dynamics in which the outcome is all DMs over-appropriating and Figure 3.10b shows the alternative evolution in which the outcome is all DMs taking a fair share. Multiple outcomes are observed because there are multiple strategies from which DMs can choose. Moreover, the evaluated positions

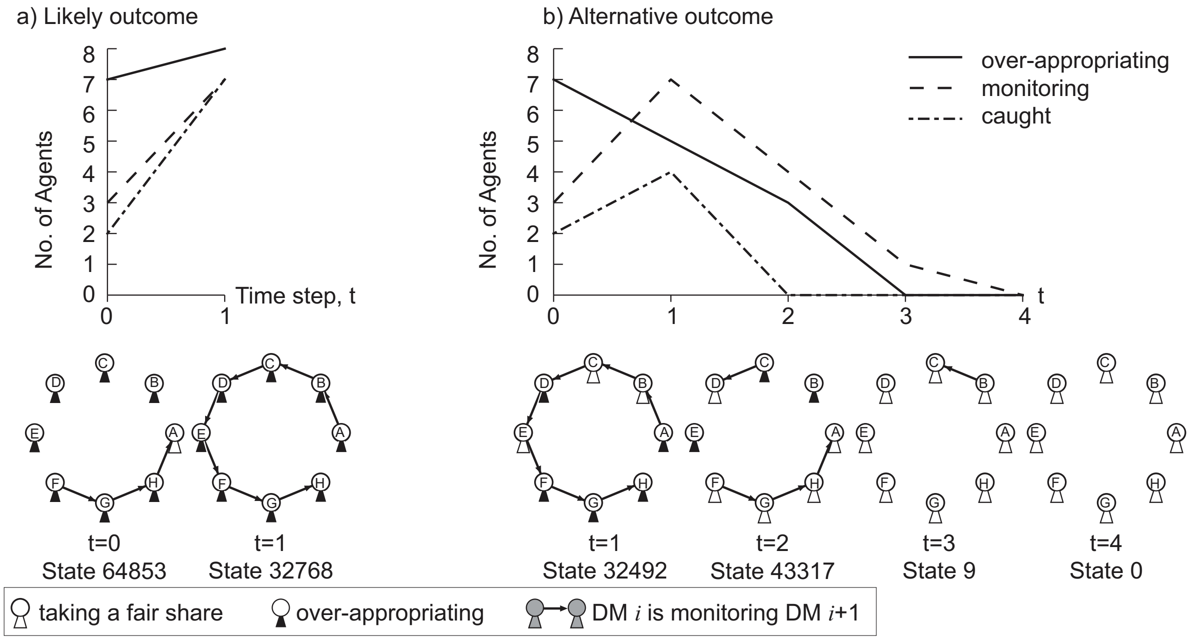
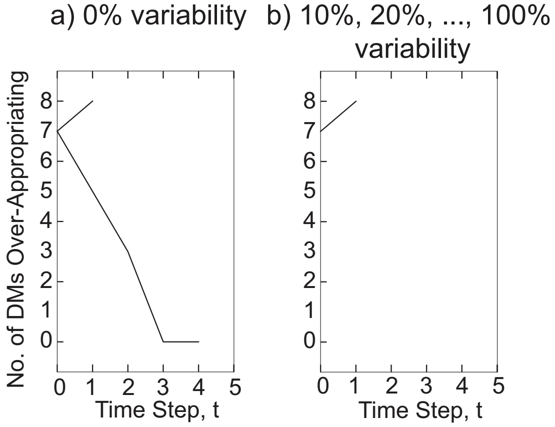


Figure 3.10: Conflict dynamics from initial state 64853 for weighting satisficers with the ECON value system.

to which these changes in strategy lead are equally preferred. The resulting trajectory in the conflict evolution depends on how strategies change from the initial to the first time step.

The change in the number of over-appropriators over time is plotted for the two outcomes in Figure 3.11a. After 100 simulation runs, 99% end with all DMs over-appropriating and 1% ends with all DMs taking a fair share, as shown in Figure 3.11c. To demonstrate the effect of perturbing the value system inputs, the pair-wise comparisons of the ECON value system were perturbed by gradations of 10% up to 100%. As can be seen in Figure 3.11b, only one outcome was reachable for variability of 10% or greater.



Distribution of end states for 100 runs

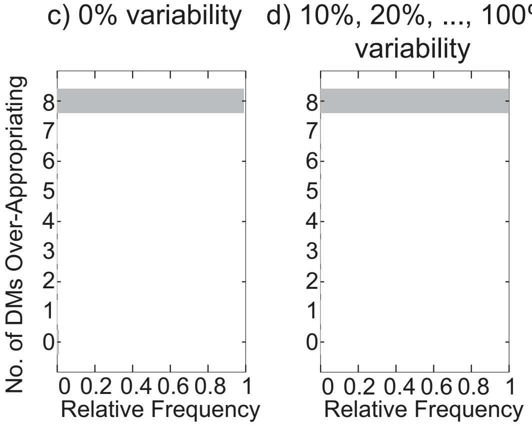


Figure 3.11: Timeline of the number of over-appropriators and distribution of end states from initial state 64853 for weighting satisficers with variable inputs for the ECON value system.

The outcome in which all DMs over-appropriate was reached regardless of the degree of perturbation. Hence, this outcome is robust under uncertainty in value system inputs. On the other hand, the outcome in which all DMs take a fair share is very sensitive. This outcome was no longer reachable because, given the perturbed inputs to the value system model, the resulting preferences were no longer indifferent among multiple strategies. Hence, a slight change in the pair-wise comparisons made this outcome unreachable.

On the whole, the satisficing comparison scheme is less sensitive than the optimizing comparison scheme when presented with variable inputs to the value system model. As shown in Figure 3.11, the satisficing scheme removed a sensitive outcome but identified a robust outcome under varying degrees of perturbation. Contrastingly, the optimizing scheme introduces new outcomes when value system inputs are perturbed. Figure 3.12 shows the change in the conflict dynamics as the degree of perturbation is increased.

For 0% and 10% variability, the outcome is the same as with no perturbation for all 100 simulation runs. The end states cycle between five and six DMs over-appropriating. As the variability is increased, different trajectories are introduced. Gradually, the distribution of end states flattens out as the original outcome loses its dominance over other outcomes.

Based on the results of this sensitivity analysis, the outcome obtained from the optimizing comparison scheme is robust to a variability of 10% in the value system inputs. Gradually, the conflict dynamics diversify as more perturbations are introduced. Hence, the optimizing comparison scheme is a suitable modeling technique when pair-wise comparisons of objectives and attributes are certain. However, the satisficing comparison scheme is a

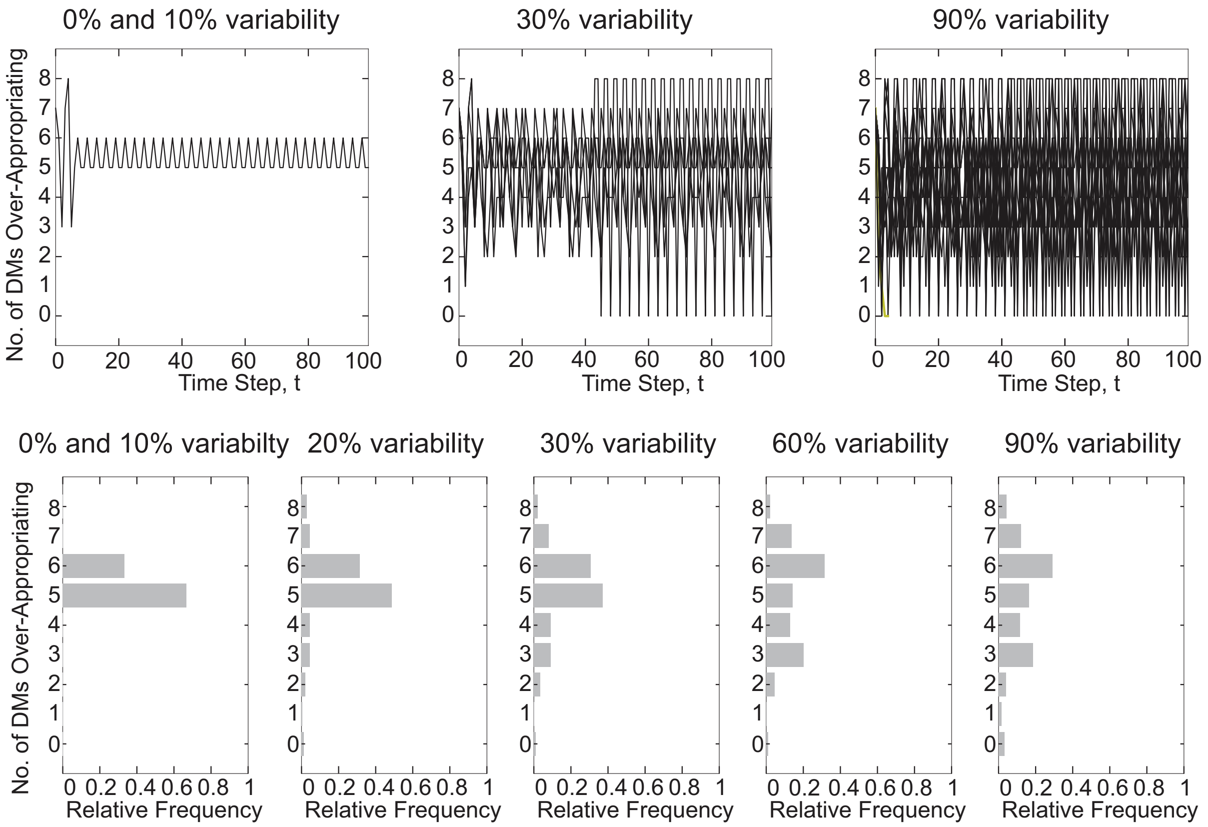


Figure 3.12: Conflict dynamics and distribution of end states from initial state 64853 for weighting optimizers with variable inputs for the ECON value system.

useful alternative when the value system inputs are uncertain, although very different dynamics would emerge.

A full sensitivity analysis can be carried out in which all possible initial states would be analyzed in order to validate the robustness of a model. An analyst faces a significant challenge, however, in determining which sensitivity tests to run and how to display the results in a meaningful manner for a DM or policy maker. To a large extent, the inputs and parameters that should be varied will depend on the knowledge of the real-world situation that the model attempts to simplify. Ideally, the proposed model would be relatively insensitive to small changes in inputs and parameters for which the values are uncertain. On the other hand, it is recognized that this particular conflict model and others like it are nonlinear. Hence, a significant change in the output due to a small change in the input would not necessarily mean that the model is an invalid representation of reality. Instead of focusing on the predictive usefulness of the model, an analyst would emphasize the practicality of using the model to explore different futures and possibilities. In order to communicate sensitivity and exploratory results, a direction for future research is data visualization techniques for conflict models.

3.4.5 Uncertainty analysis

At this time, the preferences construction methodology and agent-based framework is deterministic. The present work provides a methodology and framework for deterministic assessment in a simulated environment of policies that are aimed at tackling challenging CPR and other resources problems. In the real world, however, the moment that a CPR will collapse is unknowable and such uncertainty or beliefs regarding when a CPR will collapse can influence a DM’s preferences. In future work, the proposed preference construction methodology and corresponding ABMS platform can be extended to undertake probabilistic assessment by incorporating uncertainty in decision making. In addition to uncertainty in when the CPR is going to collapse, there are a number of other uncertain aspects such as how much information participants have with regard to other participants’ past decisions and current preferences. The preferences methodology and ABMS platform can be expanded to take into account these uncertain factors.

3.5 Summary of contributions

Strategic governance involves designing rules or policies that align with multiple participants’ values and take into account strategic considerations among participants whose actions, in some way, need to be influenced in order to achieve SoS goals, such as cooperation for mutually beneficial outcomes. This work makes a contribution to strategic governance with a SoS engineering methodology to obtain ordinal preferences over states from values. The process involves hard thinking about values in terms of fundamental objectives, attributes and criteria to measure the degree to which an objective has been achieved. A hierarchical approach is applied to obtain relative importance of objectives and attributes. Depending on characteristics of a DM, such as whether she seeks to satisfice or optimize and whether she prioritizes or makes tradeoffs, different schemes are invoked to obtain preferences based on how states perform on the specified attributes and how the particular DM values a significant change in these attributes.

By obtaining ordinal preferences in the systematic manner presented in this chapter, preferences can be generated efficiently for a large number of states with a nominal level of input required from each DM. Moreover, preferences can be constructed dynamically. Within an agent-based framework for modeling cooperative and competitive behaviour (Bristow et al., 2013a), strategic interactions among DMs with various preferences can be simulated. The simulation results are particularly instructive for strategic governance. In conjunction with empirical and field studies, the agent-based framework and preference constructions methodology can be employed to test rules under a wide range of conditions and put systematic policy design into practice.

In the next chapter, development of the agent-based framework for modeling cooperative and competitive behaviour under conflict is presented. Further specifications of different decision rules are provided and the effects of strategic interactions on the outcomes of a conflict are modeled and simulated. ■

Chapter 4

Complex Systems Models of Strategic Interactions

In this chapter, a novel agent-based framework for modeling competitive and cooperative behaviour under conflict is proposed. The novelty of this particular framework is the formulation of decision rules to model agents with the capacity to view their individual situation from a system's perspective and to make a decision that considers countermoves of other DMs. Formalized decision rules are developed to utilize knowledge of preferences in a manner that allows agents to anticipate consequences of their decisions in combination with other agents' actions. As recommended by Hipel and Fang (2005), GMCR solution concepts are extended for incorporation into agent-based decision methods. A general formulation of decision rules are presented for GMCR (Fang et al., 1993) solution concepts, such as Nash stability (Nash, 1950, 1951), general metarationality (GMR) (Howard, 1971), symmetric metarationality (SMR) (Howard, 1971), and sequential stability (SEQ) (Fraser and Hipel, 1979, 1984). Within the frameworks of ABMS and GMCR, proposed policies or rules can be tested for effectiveness in the governance of agents' interactions in a SoS.

The overarching motivation for this work is provided in Section 4.1. In Section 4.2, the proposed agent-based framework is outlined and in Section 4.3, the theoretical development of decision rules for agents is presented. In Section 4.4, a practical application of the strategic decision rules is demonstrated for a Tragedy of the Commons-type policy challenge. Section 4.5 concludes the chapter with a summary of contributions of this work. Initial findings from this research were presented earlier at the 2012 Group Decision and Negotiation conference in an extended abstract (Bristow et al., 2012b). Some research results also appear in an article by Bristow et al. (2013a).

4.1 Motivation

The collapse of a common resource, the segregation of nations, and the evolution of cooperation and norms are systemic responses which, as demonstrated by Hardin (1968), Schelling (1969), and Axelrod (1997), respectively, could arise from the interactions of individuals who follow seemingly simple, and individually-focused, decision rules. This process of emergence, which is noted by Schelling (1978) as micromotives leading to macrobehaviour, characterizes, among other features, classes of systems called complex engineered systems (Braha et al., 2006), complex adaptive systems (Miller and Page, 2007), as well as systems of systems (Jamshidi, 2009). The study of such systems is highly warranted because an understanding of them may be utilized for the design of policies and programs that seek to effectively govern individuals' actions such that desired systemic responses are achieved to meet overall SoS goals.

A popular methodology for studying emergence in complex systems is agent-based modeling and simulation (ABMS) (Danielson, 2002; Epstein, 2002; Read, 2002). Its popularity is steadily increasing, with just 63 articles prior to the year 2000 to over 3,200 articles published in the 21st century (found by searches for "agent-based model*" in the Web of Knowledge database in the respective timespans). Indeed, as of the date of this thesis, a keyword search of "agent-based" in the IEEE Xplore digital library brings forth a total of around 400 articles in journals and magazines (9% of which were published prior to 2000), in addition to over 5,300 conference publications (5% of which were published prior to 2000).

ABMS requires the definition of four items (Macal and North, 2010): 1) agents along with their attributes as objects of classes to distinguish different agent types, 2) the environment the agents inhabit and with which the agents interact, 3) methods which agents use to update their attributes in response to interactions with the environment or other agents, and 4) agent interactions which are methods that control when, how and which agents interact during the simulation. Within the agent methods are embedded decision rules, which feign a level of intelligence based on an algorithmic abstraction of human-like decision making. It is assumed that the closer the decision rules are to an actual DM's thinking processes, the more valid the model will be. Conversely, the greater the disparity between the observed and simulated systemic response, the more likely that assumptions on agents' decision rules are less valid.

An example of a simple decision rule is one that takes a measurement of an environment variable and compares the measurement value to a threshold value to select a strategy. As an example, a decision rule could be: if the percentage of neighbours who selected strategy "Y" in the previous time step is greater than 50%, then select strategy "Y". The decision relies only on the knowledge of a past event. As a result, agents are reactive. Deadman (1999), Deadman et al. (2000), and Deadman and Schlager (2002) have applied agent-based modeling techniques to simulate individual behavior and group performance in CPR management. Their research follows the work of Ostrom et al. (1994) quite closely and proposes agent-based models to simulate the same or similar experiments that were designed and conducted by Ostrom et al. (1994). In the simulations, the agents employ reactive decision rules that do not consider countermoves of other DMs in response to their own moves. Hence, the work presented here is different in that it provides agents with greater foresight and the ability to consider other agents' countermoves.

Some attempts have been made to create proactive agents with beliefs, desires and intentions (Sakellariou et al., 2008). Silverman et al. (2006) propose an intention management function linked with decision theory to model agent decision making. In a similar vein though a different approach, this work provides a general formulation for ABMS to implement agents' decision rules that anticipate future states of their world based on the knowledge of their own and other agents' options and preferences. As a result, agents' decision rules have strategic considerations. Just as a chess player looks a few steps ahead to anticipate how his opponent would move, agents may also be equipped with strategic decision making processes. Agents need to be able to consider how other agents' actions, which can be in conflict with their own actions, may affect their individual standings. Other agent-based frameworks lack techniques for modeling agents who consider moves and countermoves. Hence, as recommended by Hipel and Fang (2005), solution concepts of the Graph Model for Conflict Resolution (GMCR) (Fang et al., 1993) are extended to formulate decision rules for strategic agents. Preliminary research and results were presented at the International Conference on Group Decision and Negotiation in 2012 (Bristow et al., 2012b). Based on this preliminary work, new agent-based techniques have been developed to model conflict dynamics.

4.2 Agent-based modeling and simulation framework

Agent-based frameworks have been proposed for collaborative and coordinated activities in which agents interact to resolve conflicts, such as in multisensor networks (Hodge and Kamel, 2003), airplane collision avoidance (Šišlák et al., 2011), and smart grids (Nguyen et al., 2013). In cooperative agent-based frameworks, individual agents have intrinsic motives to work together and avoid conflicts. On the other hand, simulated worlds have been proposed for modeling human behaviour to understand conflict in a “controlled laboratory” setting (Casti, 1997). In these worlds, agents do not necessarily seek cooperative outcomes, but are beholden to their own preferences and subject to influential actions of others. Among many reasons for proposing these simulated worlds is the possibility of putting forth solutions to influence cooperation or mitigate conflicts, which Silverman et al. (2007) seek to do in role-playing sociocultural games, and Spieser and Davison (2009) demonstrate in stabilizing the psychological dynamics of crowds. Simulation is necessary because it may not yet be possible to reduce the dynamics of the system to pure mathematical forms (Epstein and Axtell, 1996; Axelrod, 1997). Moreover, simulation is useful where there are heterogeneous agents and path or context dependent processes (Marney and Tarbert, 2000).

The agent-based framework proposed in this work falls into the category in which agents are not necessarily intrinsically motivated to cooperate. Depending on external influencing conditions, however, they display competitive and cooperative behaviour to achieve individual goals. The cumulative actions of all of the agents are evaluated on a societal system level to render account of the overall SoS behaviour. The current methodology utilizes GMCR solution concepts that only require ordinal preference information, which is different from the decision making methods of Silverman et al. (2006) who employ a stress-constrained subjective-expected utility formulation for determining an agent’s best response. However, the proposed methodology may be a potential alternative implementation for the intention management module of Silverman et al.’s (2006) unified agent-based architecture.

Figure 4.1 illustrates the proposed agent-based framework for modeling competitive and cooperative behaviour under conflict. Agents are models of DMs. At the core of each agent is a GMCR as a world representation of interactions among agents and basis for decision

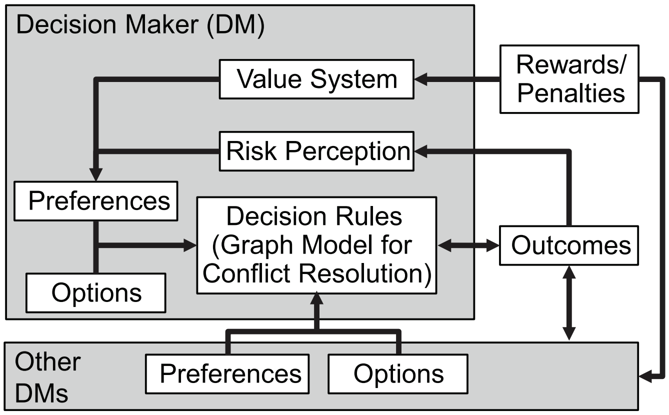


Figure 4.1: Proposed agent-based framework for modeling competitive and cooperative behavior under conflict.

making. Essentially, each agent has options. Cumulatively, the selection of options by all agents results in an outcome or state. Agents have preferences over states. Equipped with a sense of the current outcome of agents' interactions, and knowledge of options and preferences of oneself and others, an agent organizes this data into a GMCR. Then, an agent can invoke a decision rule to select his strategy which in turn affects the future outcome. In Section 4.3, GMCR and associated decision rules are formally defined.

Furthermore, each agent constructs his or her preferences dynamically. Preferences are intrinsically influenced by a value system and risk perception of an agent and extrinsically motivated by factors beyond an agent's control, for example, rewards and penalties set by authorities. A preferences construction methodology which derives preferences directly from a value system is developed by Bristow et al. (2012a, 2013b) and presented in Chapter 3 of this thesis and utilized within this framework. However, risk perception is not yet taken into account in the preferences construction methodology (Bristow et al., 2012a, 2013b).

The proposed framework provides a standardized way to model dynamic strategic interactions in an agent-based model. Since it encompasses GMCR, which is a systems methodology, the agent-based framework also maintains a general nature which can handle most types of conflicts among multiple agents insofar as the basic data on options and preferences are obtainable.

4.3 Formulation of agent decision rules

A variety of models of decision making behaviour have been developed for GMCR (Fang et al., 1993), which is a methodology for modeling and analyzing DMs' interactions in a strategic conflict. The modeling steps include: 1) identifying DMs (individuals or groups that can make a decision to affect the outcome of a conflict), 2) listing DMs' options, 3) specifying feasible states (also referred to as outcomes or scenarios) and allowable moves, and 4) determining DMs' preferences, which are relative and can be fuzzy (Bashar et al., 2012) or include strength of preference (Hamouda et al., 2006). With the above information and different definitions of decision making behaviour called "solution concepts", individual and coalition stability analyses determine which states are stable for all DMs, thereby pointing to potential resolutions or equilibria to a conflict. As GMCR solution concepts model strategic behaviour, they provide a theoretical foundation for formulating decision making rules for agents. The solution concepts model proactive behaviour akin to how a chess player envisions consequences of possible moves.

The decision support system GMCR II (Fang et al., 2003a, 2003b) provides a participant in a strategic conflict or a third party analyst with the tools to model and analyze a conflict at a certain point in time. In contrast, this work contributes to the development of a simulation platform to study the conflict dynamics of a system of agents in a strategic conflict. This involves specifying how agents' strategies may change over time for varying influencing factors such as policies, organizing processes, or norms. In this section, agent decision rules based on different GMCR solution concepts are operationally defined for a dynamic environment.

In a strategic conflict, DMs may invoke different decision making characteristics such as foresight, a willingness to accept strategic risk, and knowledge of others' values. Table 4.1 provides an overview of the solution concepts and the decision making behaviour that they model (Fang et al., 1993, 2003b). Foresight refers to whether a DM considers the countermoves of other DMs and the number of move-countermove cycles. Strategic risk is present when a DM tries to improve from the status quo state but other DMs could sanction this move. As a result, it is possible for the particular DM to end up in a less preferred state.

Table 4.1: Solution concepts and decision making behaviour.

Solution Concepts	**Foresight**	**Strategic Risk**	**Dis-improvement**	**Knowledge of Others' Preferences**
Nash stability (Nash, 1950, 1951; Von Neumann and Morgenstern, 1944, 1953)	Low	Ignores risk	Never	Unknown
General metatrationality (Howard, 1971)	Medium	Avoids risk	By opponents	
Symmetric metarationality (Howard, 1971)				
Sequential stability (Fraser and Hipel, 1979, 1984)		Takes some risk; satisfices	Never	Known

Disimprovement refers to whether a DM would unilaterally move to a less preferred state. For some solution concepts, a DM needs to know other DMs' preferences.

Stability definitions incorporate these characteristics into a model of behaviour. GMCR solution concepts (Fang et al., 1993) utilize these definitions to determine operationally whether states or potential outcomes in a conflict are either stable or unstable. If a state is stable for all DMs, then the state is an equilibrium. An equilibrium state is a possible resolution of the conflict. The analysis is, however, static. In the following subsections, the definitions of GMCR solutions concepts are extended to simulate dynamics of a conflict. That is, from a given initial state, how would the conflict evolve over time?

4.3.1 Graph model structure

A conflict involves DMs who can affect the state of a conflict. Feasible states of a conflict can be described by the strategies of DMs (e.g. all DMs choose diplomacy) or by the consequence(s) of DMs' strategies (e.g. a nuclear winter due to launching nuclear war). By virtue of having more than one strategy, a DM can change the state of a conflict by changing his strategy. A change in one's strategy when all others' strategies are constant is a unilateral move (UM) from an initial state to a destination state. A multilateral move by a group of

DMs is a sequence of UMs made by more than one DM. No DM is allowed to make more than one move consecutively. Movements occur because each DM has a personal preference from one state to another. A unilateral improvement (UI) for a DM is a UM in which the DM prefers the destination state over the initial state. A multilateral improvement for a set of DMs (not in a coalition) is a multilateral move composed of UIs by DMs.

A graph model for conflict resolution and related concepts are formally defined as follows.

Definition 4.1 A graph model for conflict resolution is a structure $G = \langle N, S, \{\succcurlyeq_i, A_i, i \in N\}\rangle$, where N is a non-empty, finite set, called the set of DMs; S is a non-empty, finite set, called the set of feasible states; $\succcurlyeq_i$ are relative preferences over pairs of feasible states for DM i such that $s_1 \succcurlyeq_i s_2$ means that DM i prefers s_1 to s_2 or is indifferent between the two states, and $A_i \subseteq S \times S$ is the set of directed arcs, which contain the movements in one step controlled by DM i.

Definition 4.2 DM i's directed graph is denoted as $G_i = (S, A_i)$, where S denotes the vertex set and $A_i \subseteq S \times S$ denotes the arc set.

Definition 4.3 An integrated graph is a union of all DMs' directed graphs denoted as $IG = \{G_i: i \in N\} = (S, A)$, with the vertex set S and the arc set $A = \{A_i: i \in N\}$.

A graph model assumes that the set of feasible states are already known. Feasible states can be generated using option form (Howard, 1971; Fraser and Hipel, 1984; Fang et al., 2003a, 2003b) or by some other logic followed by a modeler in consultation with DMs. If option form is employed, then a DM's strategy is a combination of options selected by the DM and a state is a combination of all DMs' strategies. Formally, options are related to strategies and strategies to states as explained below. Also defined below are unilateral and multilateral moves from one state to another, and preferences along with unilateral and multilateral improvements.

Definition 4.4 Let $O_i = \{o_{ij}: j = 1,2, \dots, m_i\}$ denote the option set of DM i for $i \in N$, where o_{ij} represents the jth option controlled by DM i and $m_i = |O_i|$ denotes the number of options available to DM i. A strategy for DM i is a mapping $g: O_i \rightarrow \{0,1\}$ such that $g(o_{ij}) = 1$ if

DM i selects option o_{ij}, or $g(o_{ij}) = 0$ otherwise. Let $O = \bigcup_{i \in N} O_i$ be the set of all options of all DMs, where $h = \sum_{i \in N} m_i$ is the total number of options for all DMs. A state is a mapping $f: O \to \{0,1\}$ such that $f(o_{ij}) = 1$ if $g(o_{ij}) = 1$, or $f(o_{ij}) = 0$ otherwise, for $i \in N$. Let s denote a state expressed by the h-dimensional column vector f_s. Let g_i^s stand for DM i's strategy corresponding to state s.

In other words, DM i has m_i options and each option is mapped to either "0" or "1", where a "0" means that DM i does not select the option and "1" indicates that DM i chooses the option. Hence, each state is a binary number which can be transformed into a decimalized number with the low-order digit as the top element of the state vector f_s.

Definition 4.5 Let $S = \{s_1, s_2, \dots, s_{n_s}\}$ be a set of states (outcomes, scenarios) of which any pair can be compared by DM i, where n_s is the number of states. Let $\succcurlyeq_i$ denote the DM i's (strict) preference ($\succ_i$) and indifference ($\sim_i$) relations on S provided that:

(i) $\succ_i$ is asymmetric (i.e. it cannot occur that both $s_1 \succ_i s_2$ and $s_2 \succ_i s_1$),
(ii) $\sim_i$ is reflexive and symmetric (i.e. if $s_1, s_2 \in S$, then $s_1 \sim_i s_1$, and if $s_1 \sim_i s_2$, then $s_2 \sim_i s_1$), and
(iii) $\succcurlyeq_i$ is consistent and (strongly) complete (i.e. if $s_1, s_2 \in S$, then exactly one of $s_1 \succ_i s_2$, $s_1 \sim_i s_2$, or $s_2 \succ_i s_1$). (Kilgour et al., 1990)

Let $\succ_i^2$ denote a relation defined as $s_1 \succ_i^2 s_2$ if and only if (iff), for all $s_3 \in S$: $s_1 \succ_i s_3$ and $s_3 \succ_i s_2$, and let $\sim_i^2$ denote a relation defined as $s_1 \sim_i^2 s_2$ iff, for all $s_3 \in S$: $s_1 \sim_i s_3$ and $s_3 \sim_i s_2$. Preferences are transitive if $\succ_i^2 \subset \succ_i$ and $\sim_i^2 \subset \sim_i$. Intransitivity is, for example, when $s_1 \succ_i s_2$ and $s_2 \succ_i s_3$, but $s_3 \succ_i s_1$. It is assumed that preferences are transitive, such that states can be ranked by a real-valued function.

When preferences are transitive, one can use a payoff function to represent ordinal preferences. Let $V_i(s)$ represent DM i's payoff function by which states can be compared to determine preferences, such that if $V_i(s_1) > V_i(s_2)$, then $s_1 \succ_i s_2$, and if $V_i(s_1) = V_i(s_2)$, then $s_1 \sim_i s_2$. For the case of ordinal preferences, $V_i(s_1) - V_i(s_2)$ gives no meaningful information about the strength of preference. Preferences are strict ordinal if no two states are equally preferred. Beyond the ordinal information, nothing will be inferred from the values of V_i in this work.

Definition 4.6 Let $s \in S$. DM i's set of UMs from an initial state s is denoted by $R_i(s)$, where $s_1 \in R_i(s)$ if $(s, s_1) \in A_i$ and $s_1 \neq s$. Let $R_i^+(s)$ represent the set of UIs by DM i, where $s_1 \in R_i^+(s)$ if $s_1 \in R_i(s)$ and $s_1 \succ_i s$.

Definition 4.7 Let $s \in S$. For a subset of DMs (not in a coalition) $H \subseteq N$ and $H \neq \emptyset$, the set of multilateral moves by H is denoted by $R_H(s)$. Let $\Omega_H(s, s_1) \subseteq H$ represent the set of DMs who could have made the last UM in the sequence of UMs from s to s_1. Membership in $R_H(s)$ is defined inductively by

0) assuming $\Omega_H(s, s_1) = \emptyset$ for all $s_1 \in S$;
1) if $i \in H$ and $s_1 \in R_i(s)$, then $s_1 \in R_H(s)$ and $\Omega_H(s, s_1) = \Omega_H(s, s_1) \cup \{i\}$;
2) if $s_1 \in R_H(s)$, $i \in H$, $s_2 \in R_i(s_1)$ and $s_2 \neq s$, then, provided $\Omega_H(s, s_1) \neq \{i\}$, $s_2 \in R_H(s)$ and $\Omega_H(s, s_2) = \Omega_H(s, s_2) \cup \{i\}$. (Fang et al., 1993)

First, using 1), the states reachable from s by DMs in H are identified and added to $R_H(s)$; then using 2), all states reachable from states identified in 1) are identified and added to $R_H(s)$ provided that no DM could have made two moves in succession in the sequence from state s to state s_2. Step 2) is repeated until no new states are identified.

Let $R_H^+(s)$ represent the set of multilateral improvements by a set of DMs H. Let $\Omega_H^+(s, s_1) \subseteq H$ represent the set of DMs who could have made the last UI in the sequence of UIs from s to s_1. Membership in $R_H^+(s)$ is defined inductively by

0) assuming $\Omega_H^+(s, s_1) = \emptyset$ for all $s_1 \in S$;
1) if $i \in H$ and $s_1 \in R_i^+(s)$, then $s_1 \in R_H^+(s)$ and $\Omega_H^+(s, s_1) = \Omega_H^+(s, s_1) \cup \{i\}$;
2) if $s_1 \in R_H^+(s)$, $i \in H$, $s_2 \in R_i^+(s_1)$ and $s_2 \neq s$, then, provided $\Omega_H^+(s, s_1) \neq \{i\}$, $s_2 \in R_H^+(s)$ and $\Omega_H^+(s, s_2) = \Omega_H^+(s, s_2) \cup \{i\}$. (Fang et al., 1993)

Essentially, multilateral improvements are obtained in the same way as multilateral moves, except that all UMs must be UIs.

To illustrate the components of a graph model, the states of a 3-player tragedy of the commons-type conflict are first generated using option form, then displayed in graph model.

Example A Tragedy of the Commons involves multiple agents who are faced with a CPR dilemma. A CPR has two attributes: 1) difficulty excluding individuals from benefiting from the resource (difficult exclusion), and 2) an individual's use of the resource diminishes the benefits available to others (high subtractability) (Ostrom, 1990; Ostrom et al., 1994, 1999). A CPR dilemma arises when the strategies of individuals – subject to a particular configuration of the physical system, technology, rules, market conditions and personal attributes – lead to suboptimal outcomes and there exists at least one set of feasible coordinated strategies that lead to a more advantageous outcome for all individuals (Ostrom, 1990; Ostrom et al., 1994, 1999). CPR dilemmas span from the local level in the management of fisheries, watersheds, and forests (Ostrom et al., 1994) to global policy domains of climate change, international groundwater basins and transnational infrastructure such as the Internet and World Wide Web (Ostrom et al., 1999), as well as maritime straits used for international navigation (Bristow et al., 2012c).

In this particular CPR dilemma, there are three DMs: $N = \{A, B, C\}$. Each DM has a single option:

$$O_A = O_B = O_C = \{o_{A1}\} = \{o_{B1}\} = \{o_{C1}\} = \{\text{contribute to the provision of a resource}\} \tag{4.1}$$

where "✓" means that this option is selected and "×" means that this option is not selected. There are a total of eight (2^3) feasible states, listed in Table 4.2. The DMs' directed graphs are illustrated in Figure 4.2, which show the moves which belong to each DM. The change in a particular DM's strategy from one state to another state can be determined by cross-referencing the state nodes in Figure 4.2 with the state numbers, which is located in the last row of Table 4.2. For example, DM B changes his strategy from "✓" to "×" when he moves from state 4 to state 2.The relative preferences listed in Table 4.2 follow the same relations established by a linear Tragedy of the Commons payoff function, illustrated in Figure 4.3 (Sober and Wilson, 1998).

Table 4.2: 3-player Tragedy of the Commons provisions conflict in option form.

DMs	Options	States, s								Preferences$\{\succ_i, \sim_i\}_{i \in N}$
A	o_{A1}: contribute	×	✓	×	✓	×	✓	×	✓	$7 \succ_A 8 \succ_A 5 \sim_A 3 \succ_A 4 \sim_A 6 \succ_A 1 \succ_A 2$
B	o_{B1}: contribute	×	×	✓	✓	×	×	✓	✓	$6 \succ_B 8 \succ_B 5 \sim_B 2 \succ_B 4 \sim_B 7 \succ_B 1 \succ_B 3$
C	o_{C1}: contribute	×	×	×	×	✓	✓	✓	✓	$4 \succ_C 8 \succ_C 2 \sim_C 3 \succ_C 7 \sim_C 6 \succ_C 1 \succ_C 5$
		1	2	3	4	5	6	7	8	

"$7 \succ_A 8$" reads "for DM A state 7 is more preferred to state 8"

"$5 \sim_A 3$" reads "for DM A state 5 is equally preferred to state 3"

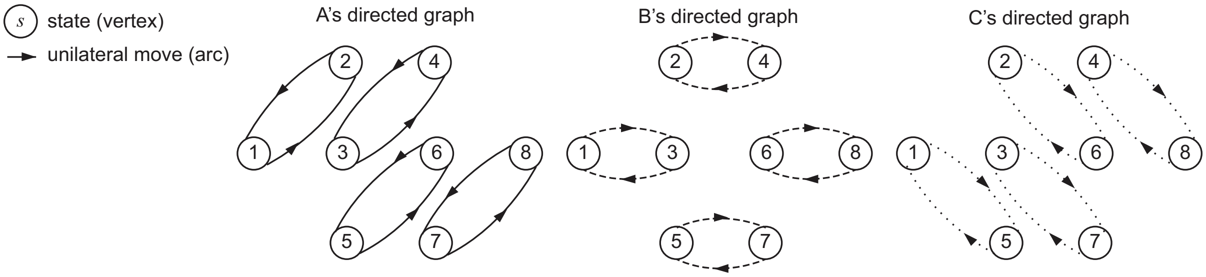


Figure 4.2: Directed graphs of 3-player Tragedy of the Commons conflict.

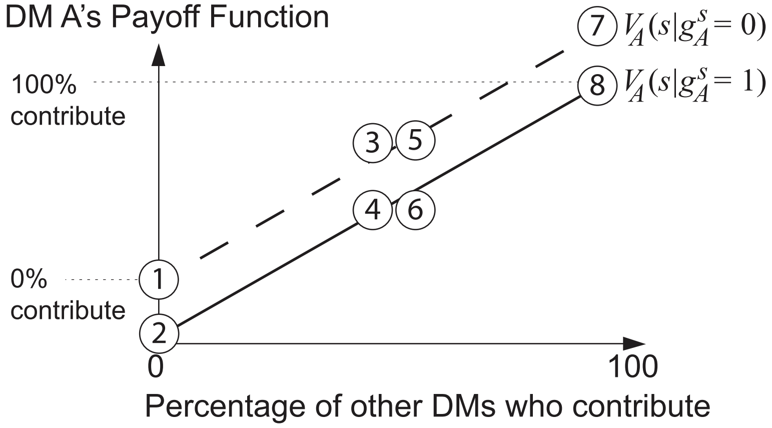


Figure 4.3: States mapped onto A's payoff function where A contributes (solid line) and does not contribute (dashed line).

DM i can either contribute to the provision of a resource $(g_i^s = 1)$ or not $(g_i^s = 0)$, where g_i^s represents the strategy of DM i corresponding to state s. DM i's payoff depends on whether other DMs decide to contribute or not. The percentage of DMs other than DM i who contribute is as follows:

$$n_1^{s,i} = \sum_{\iota \in N-i} g_\iota^s / |N - i| \tag{4.2}$$

DM i's "✗"-strategy payoff is calculated as:

$$V_i(s|g_i^s = 0) = n_1^{s,i} b_0 + \left(1 - n_1^{s,i}\right) c_0 \tag{4.3}$$

where b_0 is the individual unit benefit of not contributing while another does and c_0 is the mutual unit cost of non-contributors.

Similarly, DM i's "✓"-strategy payoff is calculated as:

$$V_i(s|g_i^s = 1) = n_1^{s,i} b_1 + \left(1 - n_1^{s,i}\right) c_1 \tag{4.4}$$

where b_1 is the mutual unit benefit of contributors and c_1 is the individual unit cost of contributing while another does not.

Equations (4.3) and (4.4) are subject to the following condition:

$$b_0 > b_1 > c_0 > c_1 \tag{4.5}$$

Conditions in (4.5) ensure that there is increasing payoff when more DMs contribute such that the payoff is greater when 100% contribute than when 0% contribute; however, there is always a higher individual payoff for one not to contribute than to contribute holding all other DMs' strategies constant. Therefore, a DM primarily prefers states where more contribute than not, and secondarily, prefers states in which he does not contribute personally. Assuming indifference toward other DMs, states with the same number of other DMs cooperating are equally preferred. This example of a Tragedy of the Commons game is used to illustrate the application of decision rules defined in the next subsections.

4.3.2 Decision rules by solution concept

GMCR solution concepts defined by Fang et al. (1993) have been used extensively for studying 2-player and *n*-player conflicts. In this work, *n*-player definitions will be utilized and modified as appropriate for an ABMS framework to determine a DM's strategy dynamically. In other words, the GMCR solution concepts listed in Table 4.1 are extended to be implemented as decision rules for agents. Part a) of definitions 4.8 to 4.11 below define Nash, GMR, SMR and SEQ stable states in GMCR, which are directly from Fang et al. (1993). These definitions are inverted to define unstable states and extended to describe selection procedures to determine a DM's best unilateral move(s) from an unstable state. The inverted definitions and selection procedures are presented in part b) of definitions 4.8 to 4.11 and constitute new contributions. All DMs are assumed to think and act independently but interact with their neighbours in order to sense the current state of a conflict. Each DM is assigned only one of the solution concepts to follow when deciding a strategy. It is assumed that DMs have complete knowledge of all feasible states defined for a conflict, their own and others' directed graphs as well as their own and others' preferences.

At time t, let $s(t) \in S$ be the current state of the conflict. DM i's UMs from $s(t)$ are $s(t+1) \in R_i\big(s(t)\big)$. Of the set of DM i's UMs, a move is a UI if $s(t+1)$ is more preferred than $s(t)$ for DM i, that is, $s(t+1) \succ_i s(t)$. The set of UIs are denoted as $R_i^+\big(s(t)\big)$, which is a subset of DM i's UMs.

DM i may consider the possible countermoves of any subset of other DMs. Let $R_{N-i}\big(s(t+1)\big)$ denote the set of all states that can result from any sequence of UMs by some or all of the DMs in $N-i$ starting at state $s(t+1)$, where no DM can move more than once in succession. Furthermore, let $R_{N-i}^+\big(s(t+1)\big)$ denote the set of all states that can result from any sequence of UIs by some or all of the DMs in $N-i$, where no DM can move more than once in succession. These sets can be constructed by performing a breadth-first search starting at node $s(t+1)$ of the integrated directed graph, $IG = \{G_j : j \in N-i\} = (S, A_{N-i})$, with the vertex set S and the arc set $A_{N-i} = \{A_j : j \in N-i\}$. The algorithm traverses the directed graph from the starting node to its children nodes and marks them. Each child node keeps track of the set of DMs who control the in-arcs that were traversed to reach it. Then, from each marked child node, its children nodes are obtained and marked provided that they are reachable by consecutive UMs (or UIs, for multilateral improvements) of more than one DM. The algorithm stops when there are no more unmarked children nodes encountered that can be legally reached, or the child node is a terminal node. Thus, the list of marked nodes forms the set of reachable states by other DMs.

Decision rules are defined formally by Zeng et al. (2007) as functions $\mathcal{P}_i: S \rightarrow S$ and specify what DM i does when a specific state arises. A DM can either stay or move. If a DM decides to move, he must also decide to which state to move. In this work, Nash, GMR, SMR and SEQ decision rules are defined for an agent to determine whether (a) to stay or move, and (b) if to move, then which strategy to select to initiate a move.

Nash decision rule

Definition 4.8a: For $i \in N$, a state $s(t) \in S$ is Nash stable for DM i iff $R_i^+\big(s(t)\big) = \emptyset$ (Fang et al., 1993).

A state is Nash stable for a DM if and only if all of the moves available to him, given that all other DM's strategies are held constant, would lead to less preferred or equally preferred states compared to the current state. If a state is Nash stable for DM i and DM i employs a Nash decision rule, then DM i does not move.

Definition 4.8b: Let $i \in N$. If state $s(t) \in S$ is Nash unstable for DM i, then DM i selects a strategy such that the expected state at the next time step is $s^*(t+1) \in R_i^+\big(s(t)\big)$ which satisfies $V_i\big(s^*(t+1)\big) = \max\big\{V(s): s \in R_i^+\big(s(t)\big)\big\}$.

If a state is not Nash stable, then a DM may change his strategy such that it leads to any more preferred state. When there is more than one state in the set of UIs by a DM, a DM must choose one path to follow. Assuming transitive preferences, if preferences are strictly ordinal, then strategy selection is unambiguous. The preference function $V_i\big(s(t)\big)$ maps state $s(t)$ to an ordinal ranking, then a DM chooses the strategy that would result in the maximally preferred state (highest ranking). If preferences are not strict ordinal and there is more than one highest ranking state, then a DM chooses from among such strategies at random since, based on this decision rule, selecting one strategy over another is inconsequential. A DM who follows a Nash decision rule ignores strategic risk since he does not consider that the other DMs would make a move that could harm his standing.

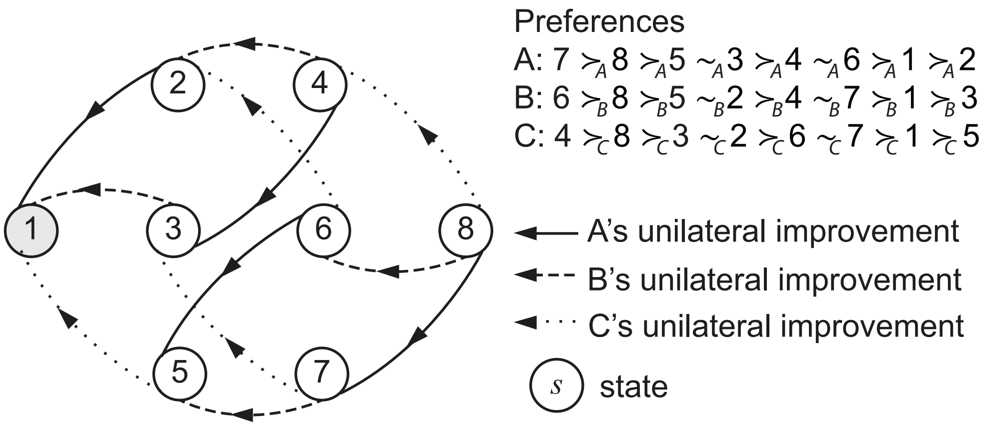


Figure 4.4: Integrated graph of all DMs' UIs, which lead to one Nash stable state in which no DMs contribute to the provision of the resource.

For example, referring to the 3-player Tragedy of the Commons conflict in Table 4.2 and Figure 4.2, the current state may be $s(t) = 8$. Suppose that DM A considers changing his strategy from "✓" to "×", which would evolve the outcome to $s(t+1) = 7$. In comparing $s(t)$ and $s(t+1)$ using his preferences derived from the function in Figure 4.3, state 7 is preferred to state 8. Therefore, DM A would move. If all DMs are Nash thinkers and follow a Nash decision rule as above, then the model reflects Hardin's (1968) Tragedy of the Commons dilemma. Figure 4.4 shows the direction of UIs for all DMs. Regardless of the initial starting node and subsequent paths through the graph, the final outcome would always be state 1, which is the only Nash stable state for any of the DMs.

General metarational (GMR) decision rule

Definition 4.9a: For $i \in N$, a state $s(t) \in S$ is general metarational (GMR) for DM i iff for every $s(t+1) \in R_i^+\big(s(t)\big)$ there is at least one state $s(t+2) \in R_{N-i}\big(s(t+1)\big)$ with $s(t+2) \preccurlyeq_i s(t)$ (Fang et al., 1993).

The logic of GMR considers the consequence of possible countermoves that other DMs can make in response to a DM's move. The DM who follows a GMR decision rule is conservative and avoids strategic risk by considering all UMs by the other DMs, even though some of these moves may be detrimental to the sanctioning DM. Hence, the particular DM would rather uphold the status quo than risk being in a worse-off state despite an initial short-term improvement. After determining the set of more preferred states compared to the current state, the DM searches for at least one future outcome which other DMs can move to that would render him in a worse-off position than at present. If at least one element in the set of other DMs' moves is less preferred than or equally preferred to the current state for each of a DM's UIs, then the current state is GMR. If a state is GMR for DM i and DM i employs a GMR decision rule, then DM i does not move.

Definition 4.9b: Let $i \in N$. If $s(t) \in S$ is not GMR for DM i, then DM i selects a strategy based on the following algorithm:

- Let $R_{i,GMR}^{+}\big(s(t)\big) \subseteq R_i^{+}\big(s(t)\big)$ be the subset of DM i's UIs such that for each $s(t+1) \in R_{i,GMR}^{+}\big(s(t)\big)$, every $s(t+2) \in R_{N-i}\big(s(t+1)\big)$ satisfies $s(t+2) \succ_i s(t)$ or $R_{N-i}\big(s(t+1)\big) = \emptyset$.
- Where $R_{N-i}\big(s(t+1)\big) = \emptyset$, $s(t+1)$ is a terminal UI. Let $E_i = \big\{e: e \in R_{i,GMR}^{+}\big(s(t)\big)\ and\ R_{N-i}(e) = \emptyset\ \big\}$ be the set of terminal UIs.
- Where $R_{N-i}\big(s(t+1)\big) \neq \emptyset$, a worst-case scenario is a state $s^* \in R_{N-i}\big(s(t+1)\big)$ which satisfies $V_i(s^*) = \min\big\{V_i(s): s \in R_{N-i}\big(s(t+1)\big)\big\}$.
- Let $W_i = \big\{s^*: s^* \in R_{N-i}\big(s(t+1)\big) \forall s(t+1) \in R_{i,GMR}^{+}\big(s(t)\big)\ and\ R_{N-i}\big(s(t+1)\big) \neq \emptyset\big\}$ be the set of worst-case scenarios.
- Let $S_{WE} = W_i \cup E_i$ be the combined set of worst-case scenarios and terminal UIs.
- DM i selects a strategy such that the expected state at the next time step is $s^*(t+1) \in R_{i,GMR}^{+}\big(s(t)\big)$ such that $s^{**} \in R_{N-i}\big(s^*(t+1)\big)$ or $s^{**} = s^*(t+1)$, and s^{**} satisfies $V_i(s^{**}) = \max\{V_i(s): s \in S_{WE}\}$.

If $s(t+1)$ and all elements in the set of $R_{N-i}\big(s(t+1)\big)$ are more preferred than the current state, then $s(t+1)$ is a state to which DM i can move and expect a better standing despite other DMs' countermoves. If $s(t+1)$ is more preferred than the current state and $R_{N-i}\big(s(t+1)\big)$ is empty, then $s(t+1)$ is a terminal UI. When there is more than one strategy to choose from, DM i decides his strategy in a two-step optimization process. First, for each move that would lead to a better state after other DMs' countermoves, the worst-

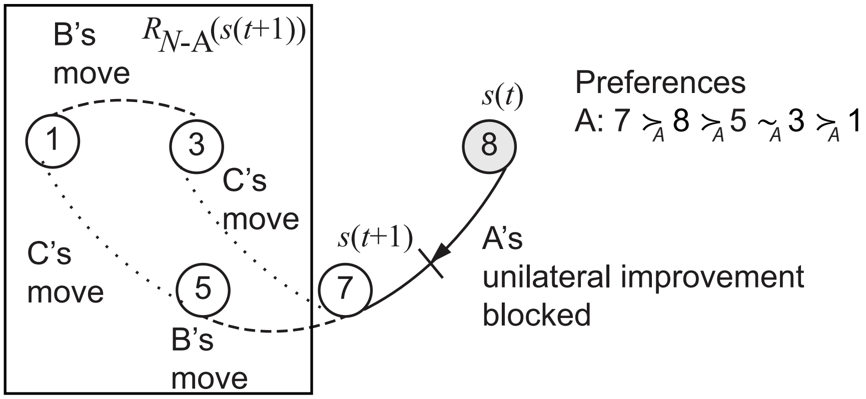


Figure 4.5: DM A decides to stay at state 8 under a GMR decision rule.

case scenarios are obtained and combined with the terminal UIs (states from which other DMs do not have UMs). Second, DM i chooses the strategy that would lead to the best worst-case scenario. If there is more than one strategy that satisfies the criterion, then DM i chooses randomly from that set.

Consider an example from the perspective of DM A in Figure 4.5; it may be tempting for DM A to move from $s(t) = 8$ to $s(t+1) = 7$. However under a GMR decision rule, DM A would also consider all possible countermoves by other DMs in any sequence. From $s(t+1) = 7$, the anticipated possible states are $R_{N-A}(7) = \{1,3,5\}$, all of which are less preferred to $s(t) = 8$, i.e., $s(t+2) \prec_A s(t), \forall s(t+2) \in R_{N-A}\big(s(t+1)\big)$. Just one less preferred state in the set R_{N-A} would be sufficient to block DM A's move. Therefore, DM A's UI is sanctioned and he would not move. Had the complete set of state R_{N-A} been preferred to the current state, then the current state would not be GMR and DM A would instead consider changing his strategy.

To illustrate the steps for selecting a strategy when the current state is not GMR, consider Figure 4.6 as an example separate from the 3-player Tragedy of the Commons conflict. State s_1 is the current state. States $\{s_2, s_3, s_4\}$ at time $t+1$ are DM i's UIs where all possible future states at $t+2$ are more preferred than the current state. State s_4 is a terminal UI. With the given preferences, the worst-case from s_2 for DM i is s_7. In considering s_3, he finds his least preferred state that other DMs could move to is s_8. Then, from the set

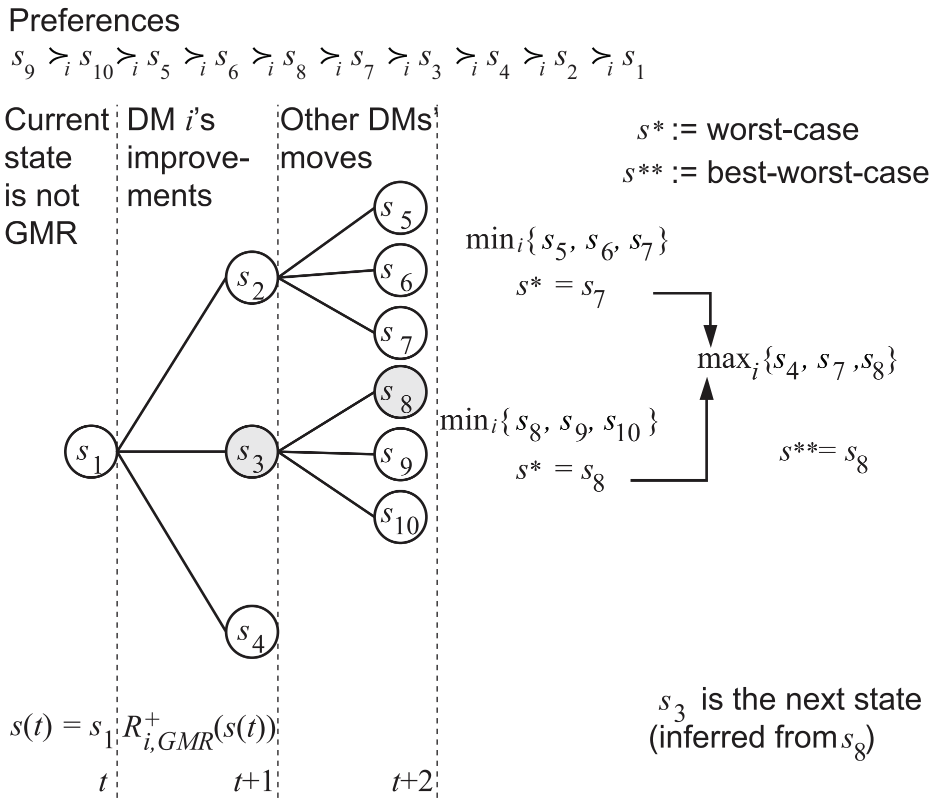


Figure 4.6: DM i would move the conflict to state s_3 under a GMR decision rule.

$\{s_4, s_7, s_8\}$, he determines his most preferred state, which is s_8. Therefore, his new strategy is to move the conflict to s_3, which is inferred from the best-worst-case scenario s_8.

Symmetric metarational (SMR) decision rule

Definition 4.10a: For $i \in N$, a state $s(t) \in S$ is symmetric metarational (SMR) for DM i iff for every $s(t+1) \in R_i^+(s(t))$ there exists $s(t+2) \in R_{N-i}(s(t+1))$, such that $s(t+2) \preccurlyeq_i s(t)$ and $s(t+3) \preccurlyeq_i s(t)$ for all $s(t+3) \in R_i(s(t+2))$ (Fang et al., 1993).

Similar to GMR, a DM, who is tempted to improve his position from the status quo, takes into account all possible combinations of UMs by the other DMs, despite the fact that some of these moves may harm sanctioning DMs. But, SMR takes GMR one step further to consider whether a DM may be able to respond and vindicate himself to a more preferred state from the current state after an initial move and any sequence of countermoves by other DMs. When a DM does not have an effective response to other DMs' countermoves, the current state is SMR. If a state is SMR for DM i and DM i employs a SMR decision rule, then DM i does not move.

Definition 4.10b: Let $i \in N$. If state $s(t) \in S$ is not SMR for DM i, then DM i selects a strategy based on the following algorithm:

- Let $R_{i,SMR}^{+}\big(s(t)\big) \subseteq R_i^{+}\big(s(t)\big)$ be the subset of DM i's UIs such that for each $s(t+1) \in R_{i,SMR}^{+}\big(s(t)\big)$, there is at least one state $s(t+3) \in R_i\big(s(t+2)\big)$ with $s(t+3) \succ_i s(t)$ for every state $s(t+2) \in R_{N-i}\big(s(t+1)\big)$ that is $s(t+2) \preccurlyeq_i s(t)$, or every state $s(t+2) \in R_{N-i}\big(s(t+1)\big)$ satisfies $s(t+2) \succ_i s(t)$, or $R_{N-i}\big(s(t+1)\big) = \emptyset$.
- Where $R_{N-i}\big(s(t+1)\big) = \emptyset$, $s(t+1)$ is a terminal UI. Let $E_i = \big\{e\colon e \in R_{i,SMR}^{+}\big(s(t)\big)\ and\ R_{N-i}(e) = \emptyset\,\big\}$ be the set of terminal UIs.
- Where $R_i\big(s(t+2)\big) = \emptyset$, $s(t+2)$ is a terminal UM by other DMs. Let $E_{N-i}\big(s(t+1)\big) = \big\{e\colon e \in R_{N-i}\big(s(t+1)\big)\ and\ R_i(e) = \emptyset\,\big\}$ be the set of terminal UMs by other DMs from state $s(t+1) \in R_{i,SMR}^{+}\big(s(t)\big)$.
- Where $R_i\big(s(t+2)\big) \neq \emptyset$, a best response to other DMs' countermoves is s^{*} which satisfies $V_i(s^{*}) = \max\Big\{V_i(s)\colon s \in R_i\big(s(t+2)\big) \cup \{s(t+2)\}\Big\}$.
- Let $B_i\big(s(t+1)\big) = \Big\{s^{*}\colon s^{*} \in R_i\big(s(t+2)\big) \cup \{s(t+2)\} \forall s(t+2) \in R_{N-i}\big(s(t+1)\big)\Big\}$ be the set of best responses to countermoves of other DMs from state $s(t+1) \in R_{i,SMR}^{+}\big(s(t)\big)$.
- Let $S_{BE}\big(s(t+1)\big) = B_i\big(s(t+1)\big) \cup E_{N-i}\big(s(t+1)\big)$ be the combined set of best responses and terminal UMs by other DMs from state $s(t+1) \in R_{i,SMR}^{+}\big(s(t)\big)$.
- Where $R_{N-i}\big(s^{+}(t+1)\big) \neq \emptyset$, a worst-case scenario is s^{**} which satisfies $V_i(s^{**}) = \min\{V_i(s)\colon s \in S_{BE}(s(t+1))\}$.
- Let $W_i = \Big\{s^{**}\colon s^{**} \in S_{BE}\big(s(t+1)\big) \forall s(t+1) \in R_{i,SMR}^{+}\big(s(t)\big)\ and R_{N-i}\big(s(t+1)\big) \neq \emptyset\Big\}$ be the set of worst-case scenarios.
- Let $S_{WE} = W_i \cup E_i$ be the set of worst-case scenarios and terminal UIs.

- DM i selects a strategy such that the expected state at the next time step is $s^*(t+1) \in R^+_{i,SMR}(s(t))$ such that $s^{***} \in R_i\left(s: s \in R_{N-i}(s^*(t+1))\right)$ or $s^{***} \in R_{N-i}(s^*(t+1))$ or $s^{***} = s^*(t+1)$, and s^{***} satisfies $V_i(s^{***}) = \max\{V_i(s): s \in S_{WE}\}$.

If the current state is not SMR, then DM i can move to a more preferred state compared to the current state after any possible sequence of other DMs' countermoves had put DM i in a less preferred state. DM i selects his strategy based on a max-min-max decision method. First, for all countermoves of other DMs, DM i determines his best response. Best responses are also compared to countermoves that have no response. Second, for each UI by DM i, the worst-case of the best responses and terminal countermoves is obtained. Worst cases are also compared to terminal UIs. Finally, DM i selects the strategy that leads to the best worst-case of the best response. If there is more than one strategy that satisfies these criteria, then DM i chooses randomly from that set.

As shown in Figure 4.7, DM B considers a UI from state 7 to state 5 and wonders whether he may be able to respond to other DMs' countermoves. He anticipates that other DMs may countermove to any of state 1, 2 or 6. Although states 2 and 6 are more preferred for DM B than state 7, state 1 is not. DM B's only response to this disimprovement is a UM to state 3, which is also less preferred than state 7. Since DM B does not have a good response, he would maintain his original strategy and not move from state 7. On the other hand, if state 3 had been more preferred, then he would have considered changing his strategy.

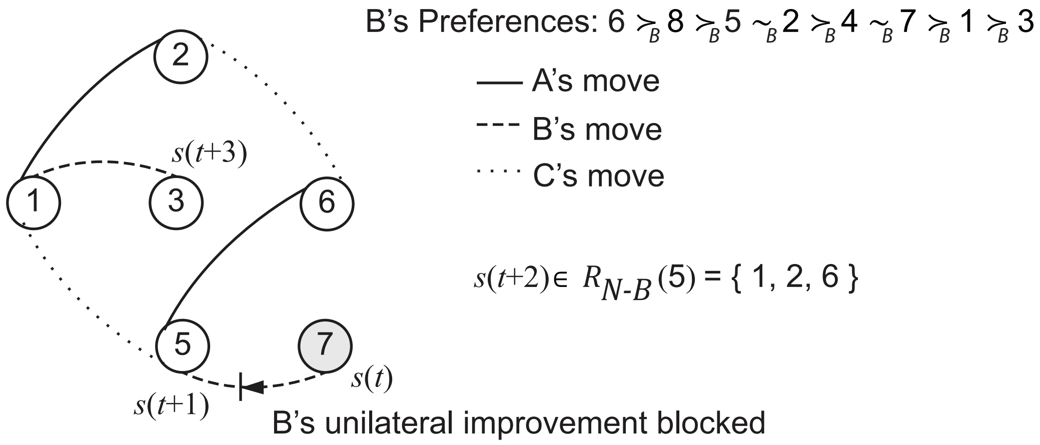


Figure 4.7: DM B decides to stay at state 7 under a SMR decision rule.

Moreover, consider another separate illustrative example in Figure 4.8 where the current state is not SMR. States $\{s_2, s_3, s_4\}$ at time $t+1$ are DM i’s UIs. From s_2, other DMs have UMs that result in s_5, which is less preferred than the current state, or states s_6 and s_7, which are more preferred than the current state for DM i. In response to the less preferred state, DM i has several ways to recover to states that are more preferred than the current state. The best of these responses are s_{11} from s_5. Although DM i has several responses to s_6, no response to this move leaves DM i in a better position than s_6. Comparing these states to s_7, the worst case, here, is s_{11} from s_2. From s_3, other DMs have UMs which result in states $\{s_8, s_9, s_{10}\}$. These states are more preferred than the current state for DM i and DM i has no UMs from these states; therefore, DM i considers the worst of these states, which in this case is s_{10}. From s_4, other DMs have no UMs; therefore, s_4 is a terminal UI. DM i compares the states $\{s_4, s_{10}, s_{11}\}$ and finds that the best scenario is s_{11}. Therefore, movement to s_2 is inferred as DM i’s strategy.

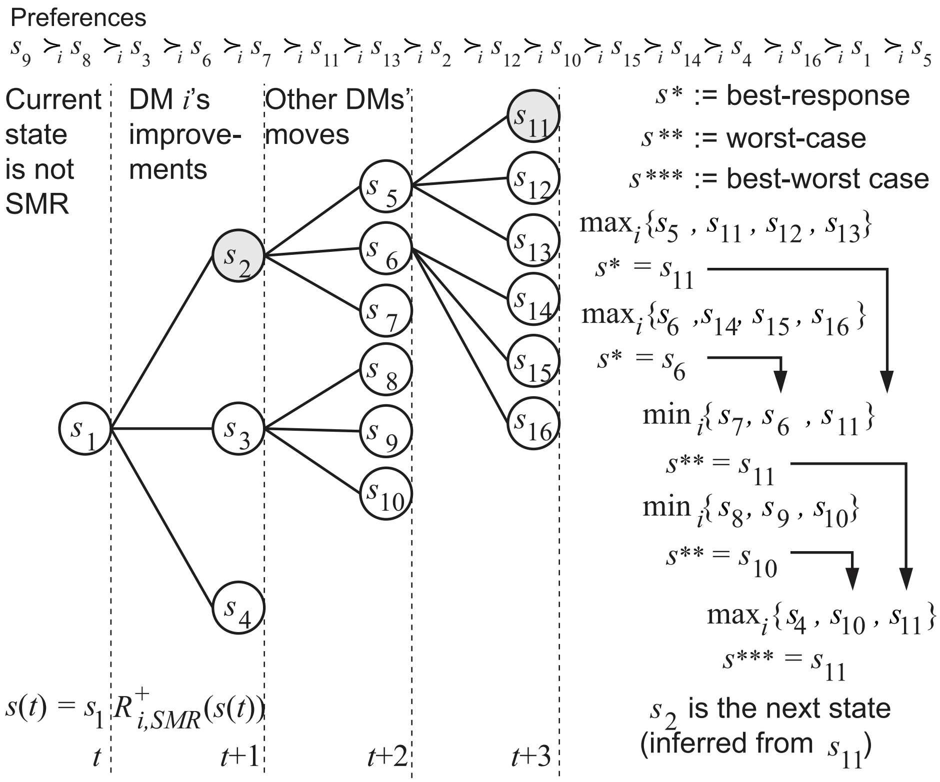


Figure 4.8: DM i would move the conflict to state s_2 under a SMR decision rule.

Sequential (SEQ) decision rule

Definition 4.11a: For $i \in N$, a state $s(t) \in S$ is sequentially stable (SEQ) for DM i iff for every $s(t+1) \in R_i^+(s(t))$ there is at least one state $s(t+2) \in R_{N-i}^+(s(t+1))$ with $s(t+2) \preccurlyeq_i s(t)$ (Fang et al., 1993).

Sequential stability is a special case of general metarationality, in which it is assumed that DMs would never disimprove. For SEQ, a DM takes some strategic risk by assuming that the other DMs will never harm themselves in the process of sanctioning. In other words, the particular DM is more optimistic about other DMs' rationality. With knowledge of other DMs' preferences, a DM can rationalize a credible response by other DMs. A DM evaluates whether expected responses could lead to a state that he prefers less than the current state. When at least one less preferred state exists for all of his UIs, the current state is SEQ. If a state is SEQ for DM i and DM i employs a SEQ decision rule, then DM i does not move.

Definition 4.11b: Let $i \in N$. If state $s(t) \in S$ is not SEQ for DM i, then DM i selects a strategy based on the following algorithm:

- Let $R^{+}_{i,SEQ}\big(s(t)\big) \subseteq R^{+}_{i}\big(s(t)\big)$ be the subset of DM i's UIs such that for each $s(t+1) \in R^{+}_{i,SEQ}\big(s(t)\big)$, either $R^{+}_{N-i}\big(s(t+1)\big) = \emptyset$ or every $s(t+2) \in R^{+}_{N-i}\big(s(t+1)\big)$ satisfies $s(t+2) \succ_i s(t)$.
- Where $R^{+}_{N-i}\big(s(t+1)\big) = \emptyset$, $s(t+1)$ is a terminal UI. Let $E^{+}_{i} = \big\{e\colon e \in R^{+}_{i,SEQ}\big(s(t)\big)\ and\ R^{+}_{N-i}(e) = \emptyset\ \big\}$ be the set of terminal UIs for which there are no multilateral improvements by other DMs.
- Where $R^{+}_{N-i}\big(s(t+1)\big) \neq \emptyset$, a worst-case scenario is a state $s^{*} \in R^{+}_{N-i}\big(s(t+1)\big)$ which satisfies $V_i(s^{*}) = \min\big\{V_i(s)\colon s \in R^{+}_{N-i}\big(s(t+1)\big)\big\}$.
- Let $W^{+}_{i} = \big\{s^{*}\colon s^{*} \in R^{+}_{N-i}\big(s(t+1)\big) \forall s(t+1) \in R^{+}_{i,SEQ}\big(s(t)\big)\ and\ R^{+}_{N-i}\big(s(t+1)\big) \neq \emptyset\big\}$ be the set of worst-case scenarios consisting of a sequences of UIs and a multilateral improvements.
- Let $S^{+}_{WE} = W^{+}_{i} \cup E^{+}_{i}$ be the set of worst-case scenarios consisting of a sequences of UIs and a multilateral improvements and terminal UIs for which there are no multilateral improvements by other DMs.
- DM i selects a strategy such that the expected state at the next time step is $s^{*}(t+1) \in R^{+}_{i,SEQ}\big(s(t)\big)$ such that $s^{**} \in R^{+}_{N-i}\big(s^{*}(t+1)\big)$ or $s^{**} = s^{*}(t+1)$, and s^{**} satisfies $V_i(s^{**}) = \max\{V_i(s)\colon s \in S^{+}_{WE}\}$.

If the current state is not SEQ, then DM i can move to a more preferred state without trepidation that other DMs' improvements would put him in a worse-off position. Of course, this faith relies on perfect information of other DMs' preferences. DM i selects his strategy by determining the worst-case scenario for each of his UIs and considering terminal UIs, finds the strategy that leads to the best-worst-case scenario. If there is more than one strategy that satisfies the criterion, then DM i chooses randomly from such a set.

As shown in Figure 4.9, the initial state $s(t) = 7$ is SEQ for DM C because DM B has a credible sanction to move the conflict to state 1, which is less preferred for DM C than state 7. On the other hand, initial state $s'(t) = 5$ is not sequentially stable for DM C because DMs

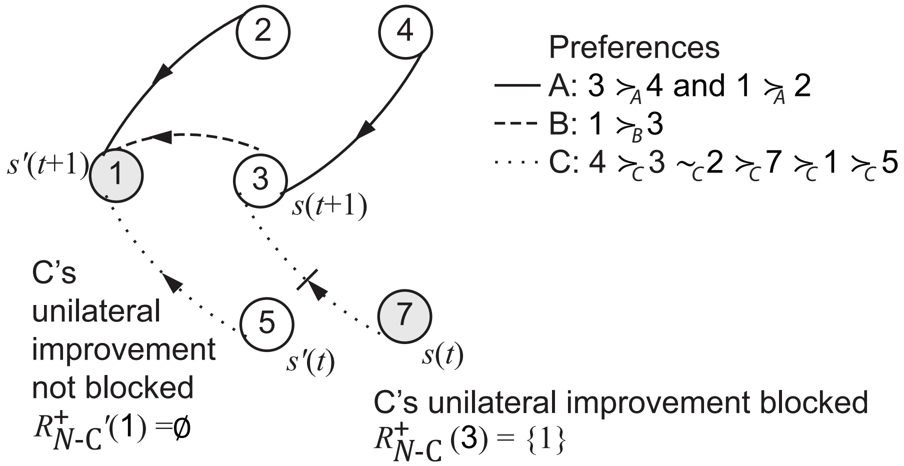


Figure 4.9: DM C would not move from state 7 to state 3 under a SEQ decision rule because DM B blocks DM C's unilateral improvement. DM C would move from state 5 to state 1 under a SEQ decision rule, since other DMs do not have a credible countermove to block DM C's unilateral improvement.

A and B do not have any credible sanctions. Even if both A and B's preferences were such that they preferred states 2, 3, or 4 to state 1, DM C would still decide to change his strategy because those states are also more preferred than state 5 for DM C. Therefore, DM C would move the conflict from state 5 to state 1.

In Figure 4.10, an example is given where there are three strategies accorded to DM i that would lead to more preferred states even after other DMs' UIs. The worst cases are found to be s_7 from s_2 and s_9 from s_3. From s_4 other DMs do not have UIs. In comparing s_4 and the worst-case scenarios, the best case is found to be s_9. Therefore, DM i would move to state s_3.

Other solution concepts can also be defined for the proposed agent-based framework. For example, if an agent is nonmyopic, it would be worthwhile to create decision rules based on nonmyopic stability (Brams and Wittman, 1981; Kilgour, 1984; Fang et al., 1993). As well, since it is possible for other agents to move simultaneously to counter a move by the original agent, it is recommended that a decision rule be formulated based on the definition

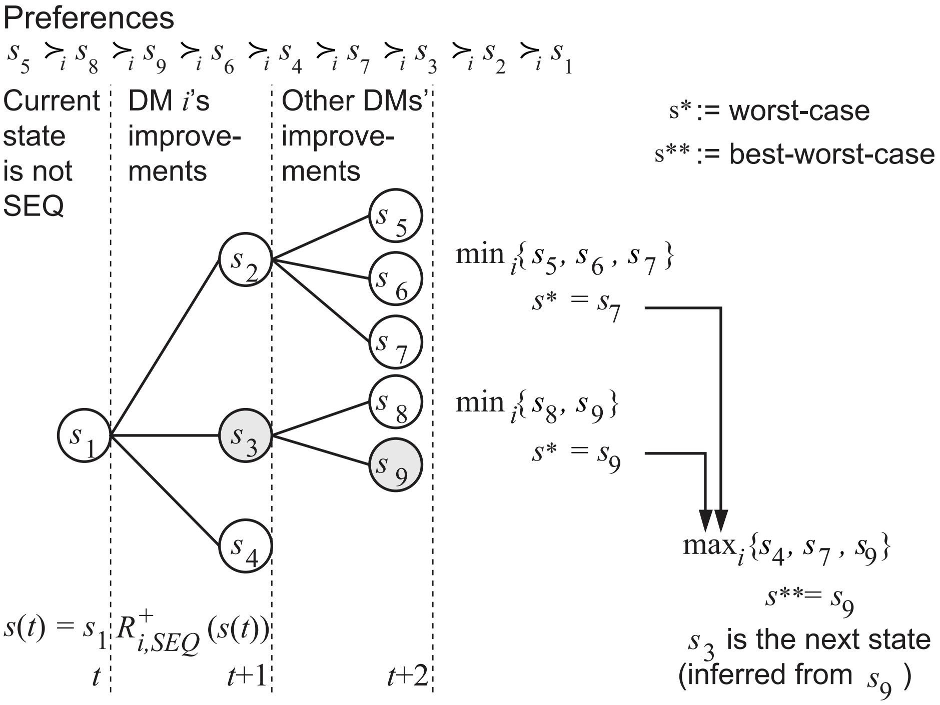


Figure 4.10: DM i would move the conflict to state s_3 under a SEQ decision rule.

of simultaneous sanctioning proposed by Stokes and Hipel (1986). Another potential characteristic of multiple-participant decision making may be asymmetric influence, such as in leader-follower relationships which may be captured in a decision rule based on the Stackelberg equilibrium (Von Stackelberg, 1934; Baser and Olsder, 1982; Fang et al., 1993). In general, the proposed agent-based framework provides a foundation on which to develop more advanced decision rules for agents as the need to make more strategic considerations increases.

4.4 The commons agent-based model and simulation

Global commons (Ostrom et al., 1999) such as the atmosphere, international waters and cyberspace present challenges that are constantly testing existing institutions. Before instituting new policies, testing policies beforehand is important to stimulate discussion and initiate action for better designed policies. In a synthesized environment of an agent-based modeling framework, a module to simulate a CPR dilemma to test and design policies is presented here. The module focuses on testing the effectiveness of policies for a population of agents who follow the different decision rules defined in subsection 4.3.2.

Although the following example explains the properties of the proposed framework for a single CPR dilemma, the framework is flexible and can be used to model different types of problems as specified by participants in a conflict, their options and preferences over conflict states. In general, the advantages of the framework are: 1) the utilization of ordinal preference information instead of utilities, 2) organization of a large number of possible conflict evolutions with a graph structure for each agent, and 3) specification of an agent's decision rule to suit individual levels of knowledge, foresight and strategic risk considerations.

4.4.1 Modeling

Agents

Agents are models of DMs with options and preferences and follow a decision rule to select their strategy. They can follow either a Nash, GMR, SMR or SEQ decision rule. In the following CPR dilemma, an agent has two roles to play simultaneously: as an appropriator and a monitor. As an appropriator, a DM takes away or appropriates a resource from a CPR. DMs can either choose to take a fair share or take more than a fair share. As a monitor, a DM monitors one other agent and, if that other agent is caught over-appropriating, effectively penalizes that agent. The options for each role are listed in Table 4.3. In effect, each agent has four distinct strategies, which are illustrated in Figure 4.11.

Table 4.3: Agent options.

Role	Option	
Appropriator	Appropriation	×: Take Fair Share ✓: Take More than Fair Share
Monitor	Monitor	×: Not Monitor ✓: Monitor

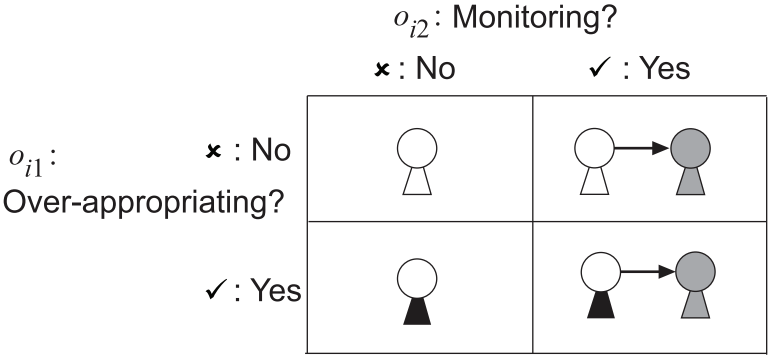


Figure 4.11: Legend of strategies.

Agents' preferences are influenced by internal and external factors. Examples of internal factors are one's values, beliefs, attitudes, and goals. On the other hand, external factors are elements generally outside of one's control such as actions of others, cost of monitoring and fine for getting caught, reward for successful monitoring, and the benefit of appropriation. Agents' ordinal preferences are obtained with a multiple objective preferences construction methodology presented by Bristow et al. (2012a, 2013b) and in Chapter 3. Essentially, states are measured on attribute scales with functions that depend on features of the state, such as how many DMs are taking more than a fair share, and exogenous factors such as the cost or benefit of one's own and others' actions. Then, using criteria, it is determined whether a given state has scored high or low compared to a specified threshold. Finally, based on a DM's value system which specifies the relative importance of attributes that describe achievement of different objectives, combinations of met and unmet criteria are mapped to a linear scale along which different states can be compared to ascertain preferences among states. Table 4.4 summarizes the parameters defined for preferences construction and the dummy numerical values used in the simulations. Using the methodology described by Bristow et al. (2012a, 2013b), it is possible to efficiently generate ordinal preferences for different types of value systems and to influence preferences by changing exogenous factors, which may be derived from policies that institute a reward or penalty for a certain action.

Table 4.4: Preferences construction parameters.

Parameter	**Value**
n: number of agents	8
$r_{\mathbb{O}_1:\mathbb{O}_2}$: pairwise comparison of economic objective to societal objective	9
$r_{\mathbb{O}_1:\mathbb{O}_3}$: pairwise comparison of economic objective to environmental objective	9
$r_{\mathbb{O}_2:\mathbb{O}_3}$: pairwise comparison of societal objective to environmental objective	1
$r_{B_{k1}:B_{k2}}$ for $k = 1,2,3$: pairwise comparison of appropriation attribute to monitoring attribute for all objectives	1
M: total benefits of everyone taking a fair share	8
L: additional benefit when one takes more than a fair share	2
F: penalty for over-appropriating	3
E: cost of monitoring	3
R: reward for catching an over-appropriator	3
C_{11}: minimum net gain of benefits from appropriation	4
C_{12}: minimum net gain of benefits from monitoring	0
C_{21}: minimum number of like-minded participants	4.5
C_{22}: minimum fraction of over-appropriators monitored	0.5
C_{31}: minimum number of participants who take a fair share	4
C_{32}: minimum number of monitors	4

Environment

In this particular model, the number of DMs is set to eight. In baseline empirical investigations presented by Ostrom et al. (1994), an upper limit of eight players invests a maximum number of tokens in a CPR, which, without explicit communication among players, was sufficient to approximate some characteristics of larger groups or conflict-ridden small groups. Therefore, eight was a reasonable number of DMs to populate the model as it is desirable to compare simulation results of agent models to empirical experiments in future work, as suggested by Janssen and Ostrom (2006). The eight agents can be visualized in an octagon as shown in Figure 4.12.

For every agent that is added the number of states is quadrupled. Hence, computational loading is kept at a manageable level by limiting the number of agents to eight. Of course, it is possible to increase the number of agents to any number. However, in order to maintain tractability and realizability of a model with a large number of agents, agents would need techniques to generalize a large number of agents or be limited to a certain number of neighbours of whom to keep track. Epstein (2006) refers to this reality as bounded rationality, the fact that agents cannot have complete knowledge of their world.

Moreover, there are empirical observations of how group size influences collective action. Agrawal and Goyal (2001) conclude by way of a game-theoretic model and empirical

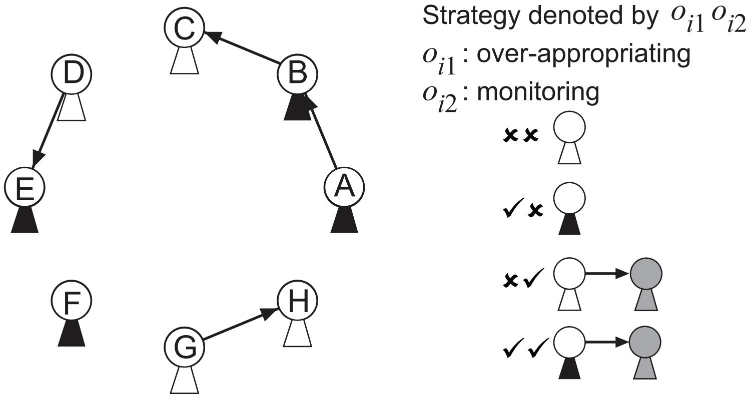


Figure 4.12: Eight agents arranged in an octagon: 4 are over-appropriating, 4 are monitoring and 2 are caught over-appropriating.

work that medium-size groups are more likely than small (< 30 members) or large groups (> 100 members) to provide third-party monitoring (the collective provision of a common good). Small groups have limited access to resources needed for collective action and large groups suffer from the difficulty in excluding errant group members (Agrawal and Goyal, 2001). On the other hand, Poteete and Ostrom (2004) propose that institutional arrangements can be designed to have a moderating effect on group size such that collective action challenges for small and large groups are addressed. Although institutional development is a collective action challenge in itself, Poteete and Ostrom (2004) affirm that the design of institutions in terms of legitimacy, effectiveness and fairness for the group is more important than particular attributes of the group. Hence, while it will be important to assess the effectiveness of proposed policies for different environments, the design of policies should aspire for legitimacy and fairness according to the value systems of participants affected by such policies.

Agent methods

Agents update their strategies using decision rules as defined in subsection 4.3.2. In order to implement a decision rule, each agent maintains his own GMCR model, as defined in subsection 4.3.1, and value system model.

Agent Interactions

An agent interacts locally with his direct neighbours through monitoring actions. If an agent monitors an over-appropriating agent in front, then he receives a reward. Conversely, if an agent over-appropriates when the agent behind him monitors, then he pays a penalty. Moreover, an agent obtains global information on how many agents are over-appropriating and monitoring and how many have been caught over-appropriating. The local and global information together provide an agent with the current state of his GMCR model, which allows him to carry out a decision rule to determine whether to maintain or change his strategy.

4.4.2 Simulations

Simulation results of the 8-player appropriation and monitoring game, in which agents strategize using one of the four decision rules formulated in subsection 4.3.2, are presented here. The study's objective is to implement the decision rules and compare their results. Hence, agents' value system models are homogeneous across all agents. Specifically, agents assume a value system modeled according to the methodology by Bristow et al. (2012a), consisting of economic, societal and environmental objectives measured on attributes relating to costs and benefits of appropriation and monitoring. Preferences are constructed using a weighted scheme based on the relative importance of objectives and attributes specified in Table 4.4. Here, an agent believes that the economic objective is nine times more important than the societal and environmental objectives, the societal and environmental objectives are equally important, and all attributes are equally important. As well, rewards, penalties and thresholds are specified in Table 4.4.

As a baseline study, all agents are first considered homogeneous in their decision rule. Heterogeneity of decision rules and other heterogeneous elements may be considered in future work. For example, Brock and Hommes (1998) have shown that by modeling heterogeneity of beliefs, extremely rich dynamics emerge. There are $n_s = 65{,}536$ (or 4^8) possible states in this game. Since agents are homogeneous, however, the order of agents does not matter. The number of unique states can be reduced to $n_u = 3317$ by considering the local states of agents. An agent can be in one of possible sixteen states in which he is either appropriating or not, monitoring or not, being monitored or not, and next to a neighbour taking more than a fair share or not. For example, as shown in Figure 4.13, states 3124 and 52273 are equivalent because the sums of local states are the same. Agents A, B, C, D, F, G and H in state 3124 are interchanged with agents F, G, H, A, C, D and B, respectively, in state 52273. To obtain the list of unique states, start with a spreadsheet of all states in their binary format. Then, count the occurrences of the sixteen local states of agents in each state. Finally, remove the entries which duplicate the patterns of occurrences of the sixteen local states.

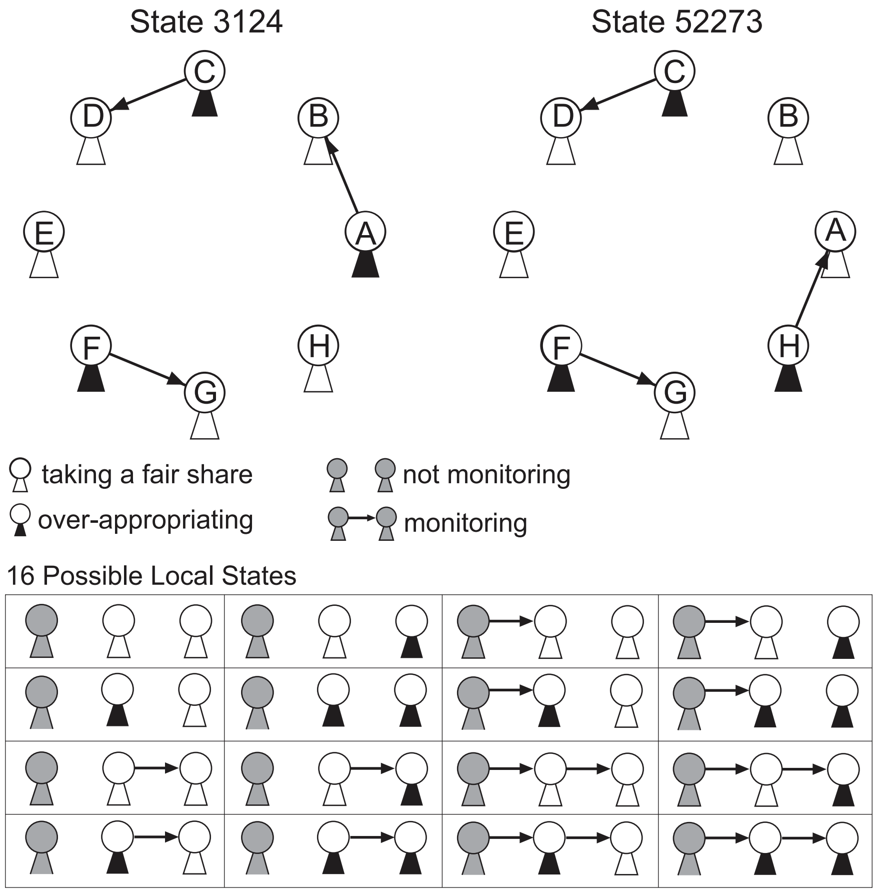


Figure 4.13: Equivalent states based on local states of agents who are all following the same decision rule and have the same value system.

Implementation

The commons agent-based model is implemented in Python 2.7 and simulations were executed on a Dual Four Core XEON 2.4 GHz processor with 16 GB of RAM. One simulation run for each unique state ($n_u = 3317$) is executed for four groups of agents: 1) all Nash agents, 2) all GMR agents, 3) all SMR agents, and 4) all SEQ agents. The results for the set of unique states are then extrapolated to the set of all states ($S = \{1,2,\ldots,65536\}$). For example, the simulation run from initial state 52273 is representative of simulation runs that would have started from seven other states (3124, 3268, 12484, 12493, 13069, 49933, and 49969).

It is possible that two simulation runs from the same initial state could lead to different outcomes. This occurs when an agent is indifferent between two states, hence, the agent chooses randomly from the available strategies. The purpose of this study is to demonstrate the implementation of the decision rules and to compare them. For these purposes, one simulation run per initial state was sufficient because the results were able to show distinct characteristics among the decision rules as shown by the plots in Figure 4.15, later in this section.

For more rigorous analysis, upon which important decisions will be made, it is essential to ensure that the results are complete (where all of the possible trajectories and outcomes are represented). More simulation runs for each initial condition would be needed. The number of required simulation runs would depend on the number of potentially distinct outcomes which can be reached and the probability of the least probable outcome. Knowing how many simulations are needed is a challenge as these are in fact not known prior to the simulation and may be the information that one is trying to gather. One possible heuristic to employ would be to adaptively determine the required number of simulations by incrementing the number of simulations until the distribution of possible conflict evolutions remains effectively unchanged.

Selected results

In Figure 4.14, a single simulation of the model is illustrated with a timeline of the following dynamic variables: the number of agents over-appropriating; monitoring; and caught. The timeline depicts how an unstable state evolves towards an equilibrium state which is stable for all agents, by way of Nash decision rules. The simulation starts at state 65045, in which five agents are over-appropriating, four agents are monitoring, and of which, three agents are caught over-appropriating. This initial state is unstable because agents A, D and E determine that they can do better by changing their strategy from taking a fair share to over-appropriating. As well, agents F and G who are caught over-appropriating and caught their neighbour in front over-appropriating find that they can do better by taking a fair share. Finally, agent H who is caught over-appropriating and needlessly monitoring assesses that he can do better by taking a fair share and by not monitoring. Consequently, the simulation moves to state 11094 at time step 1. Still, five agents are over-appropriating though they are not the same five as in the previous time step. This state is also unstable. All agents, using a Nash decision rule, change their strategies in some way to improve their standings. As a

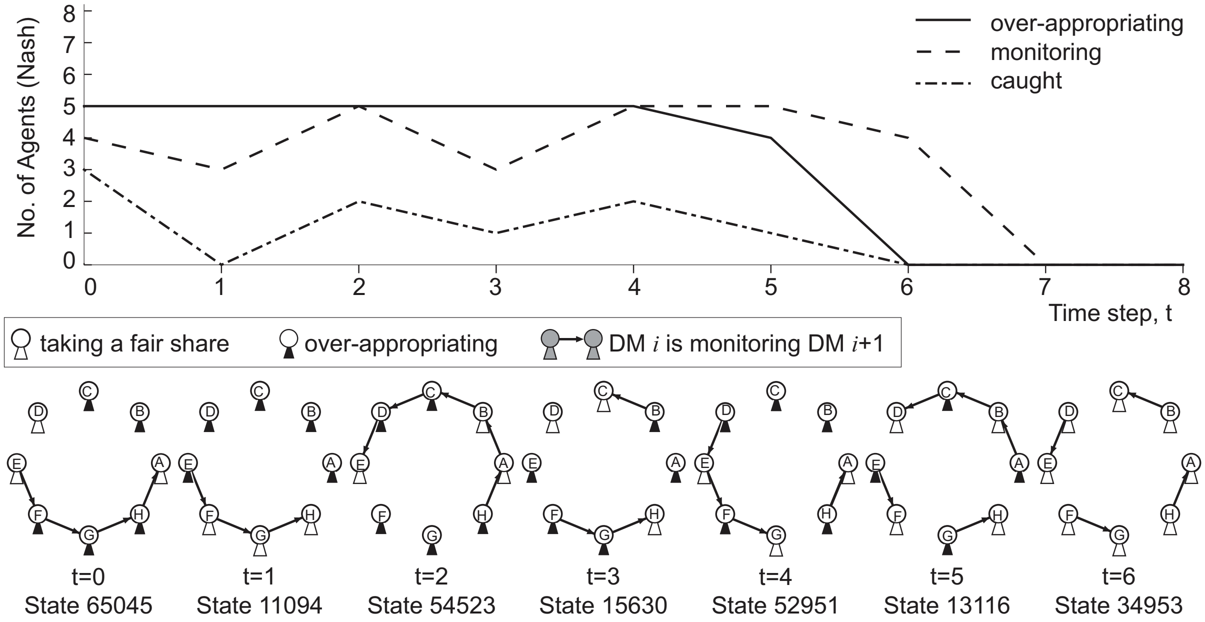


Figure 4.14: Simulation from initial state 65045 of interacting agents using a Nash decision rule.

result of the simultaneous changes in agents' strategies, the simulation changes state until a stable state for all agents is encountered. In this case the stable end state of this simulation is state 1, in which all agents take a fair share and no agent monitors needlessly. In general, the only Nash stable states are those in which either all agents take a fair share and do not monitor or all agents over-appropriate whether agents monitor or not.

In Figure 4.15, the appropriation dynamics of the commons agent-based model are presented for Nash, GMR, SMR and SEQ agents. Figure 4.15a shows the distribution of all states, $n_s = 65{,}536$, over the possible scenarios of the number of agents over-appropriating. The distribution can be expressed as the set of binomial coefficients normalized by the sum of all the coefficients, (see Chapter 3, equations (3.28) and (3.29)). If all states are equally probable to be the initial state, then $F_0(x)$ is the relative frequency where x agents are over-appropriating at the start of a simulation.

Of 65,536 states, 99.7% are destabilized by a Nash decision rule. Figure 4.15b shows the timelines of the number of agents who over-appropriate for one simulation run of each Nash unstable state. A pattern appears to emerge. From initial states where more than five agents are over-appropriating, the simulations tend to end with all agents over-appropriating; conversely, from initial states where less than five agents are over-appropriating, the simulations tend to end with all agents taking a fair share. This is not, however, a universal rule since there is one observed case that follows a path to an end state where all agents take a fair share although seven agents were over-appropriating initially.

Furthermore, Figure 4.15c shows the resulting distribution of end states in terms of the number of over-appropriating agents extrapolated to all 65,536 initial states. The distribution of end states includes all stable initial states and the end states reached from all unstable initial states. Comparing Figure 4.15c with Figure 4.15a, the extreme scenarios of either none

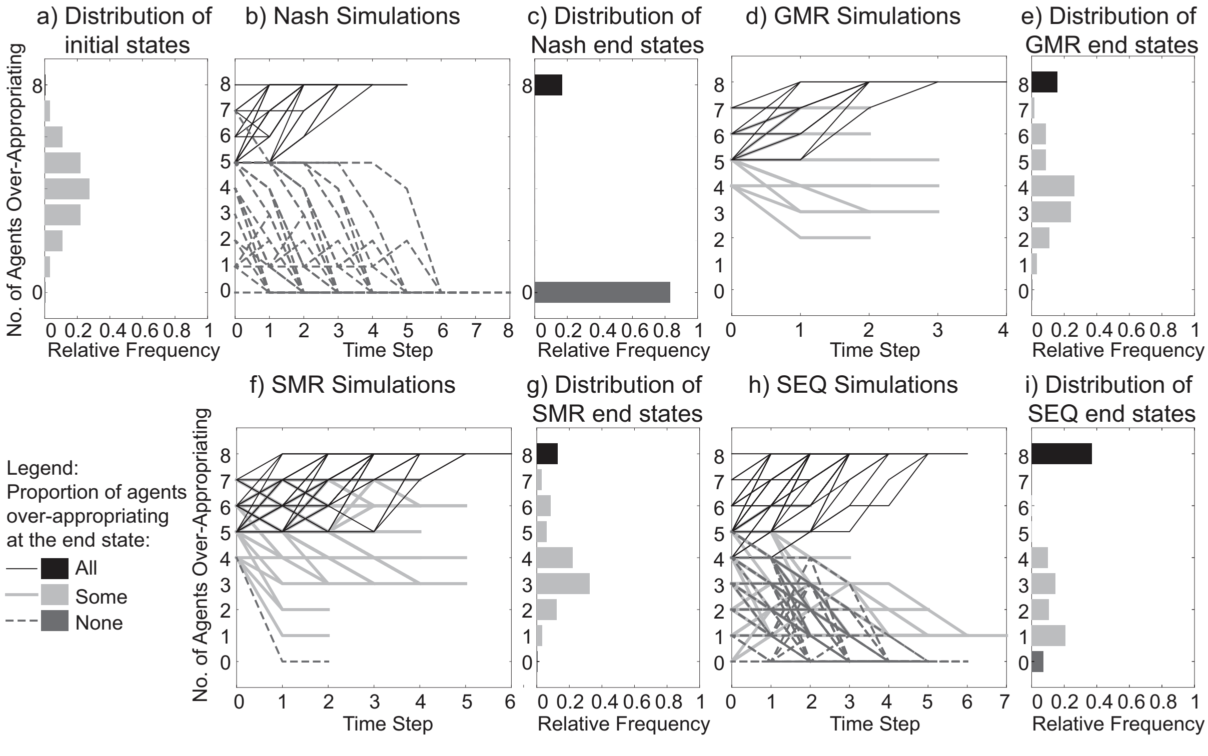


Figure 4.15: Change in the number of over-appropriating agents from initial unstable states according to Nash, GMR, SMR and SEQ decision rules and resulting distributions of stable end states.

or all agents over-appropriating, which were initially relatively infrequent, become the most frequent. Figure 4.15b can be interpreted in this way: for $n_s = 65{,}356$ (i.e., one simulation run per initial state), 83% of all observed cases end in all agents taking a fair share, while the remaining 17% end in all agents over-appropriating. In order to comprehend the results, it is necessary to understand agents' preferences. The reason why the Nash decision rule generates so few chances of having 8 DMs over appropriating is because all of the DMs are satisficers. A satisficer is satisfied when criteria are met. The state in which all DMs take a fair share and no one is monitoring achieves a DM's objectives and a unilateral move would not improve the DM's position because all criteria are already satisfied. Hence, an agent would not decide to over-appropriate even if no one is monitoring because the agent is already satisfied and no improvement would be perceived if the agent changed his strategy.

On the other hand, when all agents follow a GMR decision rule, a different pattern emerges, as shown in Figure 4.15d, in which fewer states are unstable. Of the unstable states (42% of all states), 37% evolve toward end states where all agents are over-appropriating. In the other unstable cases, the number of over-appropriators settles at a value between two and seven. In contrast to the distribution of Nash end states, the distribution of GMR end states, illustrated in Figure 4.15e, shows that a simulation of GMR agents would never end in a state in which all agents are taking a fair share, unless they started in such a state. Out of all simulations, 16% end with all agents over-appropriating. In the majority of simulations, however, GMR agents do not change their strategies, thereby reflecting conservative behaviour modeled by the GMR decision rule.

Figure 4.15f shows the appropriation dynamics from multiple unstable states for a group of SMR agents. In this particular model, the set of SMR unstable states is equivalent to the set of GMR unstable states. However, since the SMR decision rule selects a strategy differently, other simulation paths result. Similar to Nash and GMR simulations when an initial group of five or more agents over-appropriate, SMR simulations tend to evolve to a state where all agents over-appropriate. In contrast to GMR agents, it is possible for SMR agents to find a path toward a state where all agents take a fair share, though it is rare. As can be seen in Figure 4.15g, 13% of simulations end with all agents over-appropriating.

If an agent is aware of all other agents' value systems, then he can employ an SEQ decision rule. Figure 4.15h shows the resulting changes in appropriation rate when all agents invoke an SEQ decision rule. 81% are unstable SEQ states. Initial unstable states where five or more agents are over-appropriating (44% of unstable states) tend to result in all agents over-appropriating (97%). On the other hand, where three or fewer are over-appropriating (29% of unstable states), SEQ agents find a path to states where all agents take a fair share from 17% of these unstable states, whereas from the remaining 83% of these unstable states some proportion of agents over-appropriate. Compared to GMR and SMR simulations, if some agents maintain an over-appropriation strategy, it tends to be a lower proportion of agents in SEQ simulations. However, as shown in Figure 4.15i, 37% of SEQ simulations end with all agents over-appropriating, more than double the frequencies when all agents follow the other decision rules.

The above results can be interpreted in an assessment of policies designed to influence agents' behaviour towards cooperative outcomes in which agents take a fair share rather than competitive outcomes in which agents over-appropriate.

4.4.3 Testing effectiveness of policies

The agent-based model and simulations presented in subsections 4.4.1 and 4.4.2 provide a framework for emulating CPR appropriation and monitoring behaviour under conflict. They demonstrate the application of decision rules that were formulated in subsection 4.3.2. Implementation in an ABMS framework of these decision rules, which were based on GMCR solution concepts, allows simulators to populate "would-be worlds" (Casti, 1997) with strategic agents. Below, the results are discussed and an argument is presented for the relevance of applying these decision rules in agent-based models that are used to design and evaluate policies for governing CPR.

GMCR solution concepts provide realistic models of strategic behaviour that are linked directly to preferences of a DM. In this work, each agent maintains his own GMCR model. Using one of the GMCR decision rules, either Nash, GMR, SMR or SEQ, an agent determines his strategy by comparing anticipated future states using his preferences which were derived from his value system. Simulations from initial states of varying appropriation and monitoring levels find either that the initial state is stable, or a path to a stable end state from an initial unstable state. The macrobehaviour of agents – the proportion of agents over-appropriating – is thus a function of individual agents who are making strategic decisions with knowledge of who over-appropriated and monitored in the previous time step. The simulations effectively captured the difference in likely end states when different decision rules were employed.

The results of the commons agent-based model and simulations suggest what the effectiveness may be of instituting monitoring in the manner outlined in the model, whereby an agent is monitored by a neighbour. When Nash decision rules are employed by all agents, simulations end when a Nash equilibrium is reached, as determined according to the constructed preferences of the agents. As it turns out, 17% of states lead to a state in which all agents over-appropriate and the remaining 83% lead to a state in which all agents take a fair share. In contrast to an appropriation only game in which the only Nash equilibrium would be that all agents over-appropriate, the commons conflict model presented (with the invoked preferences) suggests that fair appropriation is stable and can be achieved, depending on initial conditions.

On the other hand, when agents employ GMR and SMR decision rules, the monitoring scheme imposed is in fact shown to be less effective at reaching states of fair appropriation. GMR and SMR are less effective in preventing over-appropriating than Nash is because there is more inertia on the part of each agent who would decide not to move from a state due to possible sanctioning by others. Essentially, GMR and SMR are only effective in avoiding over-appropriation if agents are initially taking a fair share. In most states, GMR and SMR agents are unlikely to change strategy. Moreover, in simulations where agents have some knowledge of other agents' preferences and use an SEQ decision rule, the monitoring scheme is ineffective when the proportion of agents over-appropriating is initially high, but somewhat effective when over-appropriating rates are initially low. Monitoring is ineffective when the number of over-appropriating agents is high because the sanctions that other agents present are not credible for SEQ agents. While SMR or GMR agents might hold their strategy at the status quo, SEQ agents change because other agents' moves are not considered a threat. Monitoring is more effective when the over-appropriating is low because of agents' value systems, in which agents are satisfied when objectives are met. Since objectives can be satisfied with everyone taking a fair share, an SEQ agent stands to disimprove if the agent and others decide to over-appropriate. Hence, it would be better on the whole to reduce or maintain low over-appropriation.

There is no evidence from the simulations that the proposed arrangement of monitoring would help agents to recover from a Tragedy of the Commons, that is, when all agents are already over-appropriating. However, the simulation results provide evidence as to the effectiveness of such a monitoring policy in enhancing the governance of a CPR appropriated by agents that employ strategic decision rules. In future studies, particulars of the monitoring policy, such as the penalty of over-appropriating and the reward of catching an over-appropriator, can be modulated to further determine regions of effectiveness/ineffectiveness. If there are regions of effectiveness, further work may be warranted to fine tune and adapt the policy for robustness against initial starting conditions and across populations of different types of strategic agents, whether by value system or decision rule.

In a real-world setting, the usefulness of the agent-based model will depend on how well it can be constrained to the particular context of the CPR environment. As a general application of the formulated decision rules, which was the scope of this work, a theoretical model was presented. This model, however, can be modified and specified to reflect a real-world CPR dilemma and validated against real-world data. Building on the foundational layer of integrating GMCR-inspired decision rules into agent-based models, future work is needed to develop specified models for real-world CPR settings for designing and evaluating proposed policies for enhancing the governance and sustainability of these important resources.

4.5 Summary of contributions

In summary, an agent-based framework for modeling conflict dynamics has been proposed. This work contributes operational methods for agent-based modeling based on solution concepts of GMCR. Decision rules for strategic agents were precisely formulated in order to simulate cooperative and competitive behaviour under conflict. This work extends GMCR solution concepts to a dynamic simulation environment to enhance the study of a conflict's evolution. Furthermore, an agent-based model that emulates CPR dilemmas on appropriation and monitoring was developed and implemented to demonstrate the feasibility and usefulness of applying the proposed framework and associated decision rules in ABMS. Different rules (conflict setups) under varying conditions may be studied with this tool. Results of such a study can be applied to the assessment of policies and institutions for governing CPR.

This work can assist systems researchers, practitioners and participants in a conflict who are interested in tackling system of systems challenges by modeling and simulating conflict dynamics with realistic strategic decision rules. The agent-based framework provides a tool to explore alternative outcomes and to determine what rules and strategic relationships help to achieve certain desirable outcomes. Participants in a conflict may want to know what they should do in a particular situation or they may want to initiate dialogue with other participants and negotiate an agreement. Different simulation experiments can be designed to provide participants with some knowledge on likely outcomes, the robustness of a strategy, or the sensitivity of a particular outcome. It is hoped that with greater understanding of strategic relationships among participants in a conflict, better decisions and improved communication may lead to desirable outcomes such that conflicts can be resolved fairly and peacefully.

As mentioned in earlier chapters, risk is an important aspect of SoS thinking and is heavily interrelated with values and complexity. Risk perception can have an impact on preferences, which in turn can affect the outcome of strategic interactions among participants. In the next chapter, a SoS engineering methodology is synthesized to integrate risk analysis with strategic considerations of participant's interactions in the management of risk in a SoS. ■

Chapter 5

System of Systems Engineering and Risk Management

In this chapter, a SoS methodology is proposed for risk analysis to establish an integrative and adaptive platform for risk management by multiple participants. The objective of this work is to consider strategic interactions among multiple participants in the management of extreme risk in a SoS, from communication to assessment to decision making and implementation. The SoS methodology utilizes a system modeling framework to model risk perception in a SoS and a GMCR component (Fang et al., 1993; Hipel et al., 2011c) to describe the strategic interactions among multiple participants. The new contribution of this chapter is the integration of risk analysis with strategic analysis techniques. Conceptual system models are utilized to map hazards and threats to consequences as a function of system state variables and risk management strategies. GMCR is a systems methodology for strategic analysis of real-world disputes and complements methods of negotiation analysis, as introduced by Raiffa (1982) and Raiffa et al. (2002), which prescribe how groups of reasonable individuals should and could make mutual beneficial collaborative decisions.

In Section 5.1, the motivation for this work is presented. In Section 5.2, knowledge gaps that arise in assessing extreme risk are defined. With different levels of knowledge and interests in the outcome of the overarching management process, participants may infer different conclusions. Based on the characteristic knowledge gaps in assessing extreme risk and the need to communicate the underlying system models used to assess and evaluate risk, a SoS methodology is developed in Section 5.3 for risk analysis. The methodology navigates through complexity, uncertainty and ambiguity of extreme risk in a SoS with system models and steers disagreements among multiple participants in a productive direction within the framework of the GMCR. Finally, the use of the methodology is illustrated in Section 5.4 with a case study on the management of maritime infrastructure systems in the Straits of Malacca and Singapore. Some of the research in this chapter was presented earlier by Bristow et al. (2012c).

5.1 Motivation

As much as can be expected, risk analysis should be unbiased and rigorous in the spirit of the scientific method. Yet, decisions made in the process of risk assessments and policies based on their results are rarely free from political, ideological, or strategic considerations – climate risk (Hultman et al., 2010) is a case in point. Given a SoS faced with the risk of an extreme event, whether as the initiating event or the result of escalating failures through the system, risk communication, assessment, evaluation and management can be particularly challenging because multiple participants are invariably involved. Participants are defined as persons who take part in the risk situation whether as a person or group who creates a threat, whether purposefully or inadvertently, suffers consequences, or acts to prevent the situation, reduce the consequences or respond to the event. Participants will have different values, attitudes and perceptions that can lead to controversy in the management of risks. Hatfield and Hipel (2002) demonstrate how different values, objectives, mandates and perspectives of risk analysts can affect the results of a risk assessment. Given this reality, risk analysis should not only be grounded scientifically but be expanded to include methods that address extra-scientific issues in how participants perceive, understand and make decisions on how to assess and manage risk. In this chapter, risk analysis is expanded to consider strategic interactions among multiple participants in the management of extreme risk in a SoS. Considering strategic interaction in risk analysis refers to developing awareness of how one's own risks are dependent on the actions of others and using this awareness to one's advantage (Goffman, 1969).

The main contribution of this work is the development of a methodology for the risk modeling and management of catastrophic SoS failure. The risk of catastrophic SoS failure can be classified as an extreme risk, which involves a rare event with catastrophic consequences. The event is expected to directly lead to or in itself be an event of catastrophic consequences. Although catastrophic consequences are expected, not all events of catastrophic consequences may be of a SoS nature. For example, sinking of a large container ship well away from any coast has potential catastrophic consequences for the crew, but as an isolated event, it is not and does not lead to a catastrophic SoS failure. However, the same incident in the heart of the Singapore Strait has the potential for system-wide impact on the global maritime transportation SoS. Blockage of the Singapore Strait may lead to a catastrophic SoS failure regionally and potentially globally. Connectivity is thus a key distinguishing feature which includes interactions of multiple systems and involvement of a diverse set of participants. To some degree it also depends on the roles of participants and recognition of a SoS.

Contentious issues arise in the risk assessment of situations of complex causal relationships and participants' interactions, poorly defined or unknown consequences, and uncertainty about the likelihood of events. These challenges present epistemological and methodological issues for risk analysts. Dealing with these issues requires a number of inherently value-based tasks in the risk analysis, such as problem formulation and criteria selection (Brunk et al., 1991). Disagreements are thus likely to occur when multiple participants with different value systems are involved. Hence, risk management of extreme events that involve multiple participants in a SoS is not immune to such controversy. Not because there is a lack of scientific rigor in the calculation of extreme risk (Haimes, 2009a), but because of the complexity, ambiguity and uncertainty of the risk situation.

Systems theory and systems analysis have been argued to be useful paradigms for assessing contentious issues in risk analysis (Hatfield and Hipel, 2002; Haimes, 2009a, 2009b, 2011; Yan and Haimes, 2011a, 2011b). A natural outgrowth of general systems theory (Bertalanffy, 1968) has been complex (adaptive) systems science (Holling, 1978; Walters, 1986; Gunderson and Holling, 2002) and system of systems engineering (Maier, 1998; Sage and Cuppan, 2001; Sage and Biemer, 2007; Jamshidi, 2009). While these emerging fields maintain conceptual roots in systems theory, they focus on a particular set of systems in which complexity, ambiguity and uncertainty are troublesome for analyzing SoS using conventional systems techniques. Considering that disagreements over risk often occur when dealing with multiple participants and cases that involve complex interactions, great uncertainties and high stakes, these emerging fields may provide further insight on addressing issues that arise in the management of extreme risk.

5.2 Knowledge gaps in assessing extreme risk

The following definitions of knowledge gaps are predicated on Kaplan and Garrick's (1981) definition of risk as a set of triplets and Haimes'(2009b, 2011) complex definition of risk. Kaplan and Garrick (1981) define risk, $\mathcal{R}$, as the complete set of scenarios where something goes wrong, s_z for all z including an "other" category which contains all scenarios not otherwise included, with each scenario characterized by the probability that it happens, p_z, and the consequence if it does happen, y_z. Mathematically, $\mathcal{R} = \{\langle s_z, p_z, y_z \rangle\}$ for all z. Note that a consequence is by definition a loss and given the decision problem, there may be more than one type of consequence to consider, hence the different types of risk such as financial risk, health risk, and safety risk. Based on this definition, an analyst would effectively be able to assess a risk given a complete table of probabilities and consequences for all of the scenarios.

How this information is obtained or becomes known, however, is another matter more recently explored by Haimes (2009b, 2011), in which consequences are determined by a system's dynamic response, based on its vulnerability and resilience, to an initiating event. As a result, Haimes (2009b, 2011) defines risk as a function of time, t, the probability of initiating events and their specificity, $\boldsymbol{u}(t)$, the states of the system, $\boldsymbol{x}(t)$ and the probability and severity of the resulting consequences, $\boldsymbol{y}(t)$. Based on this definition, quantifying risk requires knowledge of the system. Haimes (2009b, 2011) proposes that system states are central to the determination of consequences and their probabilities, and by extension to Kaplan and Garrick's (1981) definition, to the quantification of risk.

These two definitions of risk infer an epistemology of risk, illustrated in Figure 5.1, which relies on knowledge of the system, consequences and probabilities. Therefore, the difficulties of assessing risk stem from gaps in knowledge in these three respects: 1) about the system due to complexity, 2) about consequences and their magnitude due to ambiguity, and 3) about the probabilities of events from the initiating event to the consequences due to uncertainty.

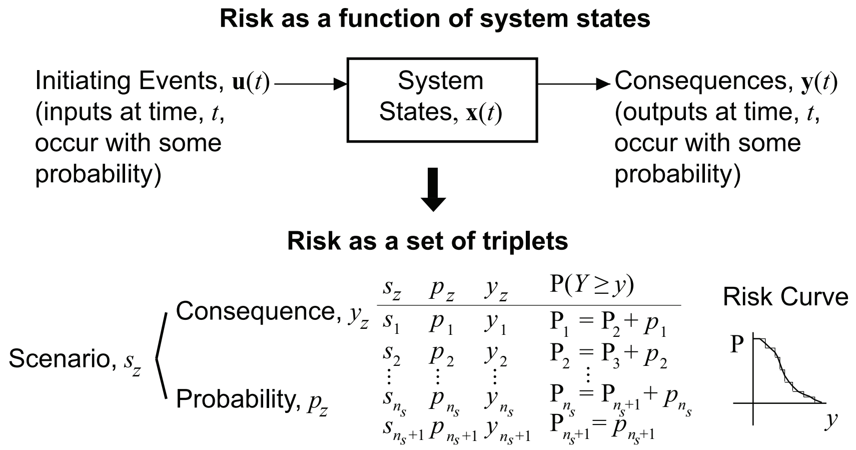


Figure 5.1: Epistemology of risk as a set of triplets (Kaplan and Garrick, 1981) and as a function of the states of the system (Haimes, 2009b, 2011).

5.2.1 System complexity

A risk analyst seeks to establish a causal relationship between one (or more) hypothesized cause(s) and one (or more) observed effect(s) of concern. As the number of causes, effects and feedback loops in the system increases, the system's behaviour becomes more difficult to predict. Moreover, multiple interacting participants who inhabit a system may produce emergent behaviour and their effects on the system's behaviour can be unpredictable. Increasing complexity presents a significant challenge to risk experts because the inner workings of a system are less obvious. Pich et al. (2002) define complexity as "an inability to evaluate the effects of actions because too many variables interact." A lack of knowledge of the system due to high complexity is an issue for risk analysts in evaluating effects to demonstrate the existence of a risk, that is, the potential of a loss due to some initiating event.

The issue for risk analysis in a SoS, however, is that multiple participants may hold a different set of objectives, concerns and preferences based on their perspectives which are equally valid for the value-driven tasks in creating a model. Depending on the perspective used to frame and formulate a problem, different models may result. Therefore, participants may have seemingly incommensurate pictures of the same system. Hatfield and Hipel (2002) demonstrate that explicitly stating the different models of the same system held by stakeholders who disagree about a risk can expose the roots of a controversy over the evaluated risk. Exposing the different definitions of the system (its boundaries, state variables, objectives and criteria) can help to resolve such controversy. To accomplish this, all participants' perspectives need to be communicated to expose different views of the system, which together are more encompassing and complex. Systems modeling can help to foster pluralistic understanding of a system with multiple models. The intent is to generate knowledge about a system among its participants.

5.2.2 Ambiguity of consequences

Stirling and Mayer (2000) define the state of ambiguity as a lack of knowledge about outcomes manifested in poorly defined outcomes. Alternatively, Pich et al. (2002) consider ambiguity as not being aware of the state of the system. Given that the severity of consequences depends on the state of the system, ambiguity in the state of the system propagates to ambiguity in the severity of consequences. Therefore, ambiguity of consequences can refer to two issues: 1) the complete set of consequences is unknown, and 2) the severity of a consequence is imprecise.

Since a risk assessment is motivated by concerns about future consequences (outcomes) of present decisions, consequences are judged by what is important to participants. Different misgivings may result in different problem formulations and system definitions that lead to selecting a subset of different indicators to measure in order to judge risk. System complexity permits ambiguity in choosing which consequences are important. Deciding which consequences are important should be done explicitly in devising multiple system models from different frames.

Moreover, the quantification of some consequences may be imprecise, especially for extreme events in which consequences are very high. Imprecision means that a range can be surmised but an exact value is not known. Imprecise measurement of consequences is an issue, independent of system definition, in deciding whether a risk is acceptable or not. Coping with ambiguity in the severity of consequences in risk management means making tough decisions in spite of thresholds and predictions by models that may have different meanings and interpretations held by participants. Negotiations are one approach that multiple participants can use to cope with ambiguity (Brugnach et al., 2011). A negotiation process assumes a willingness among participants to negotiate and helps participants to handle ambiguity by reaching an agreement that is meaningful from different frames (Brugnach et al., 2011). GMCR, as a negotiation tool (Kilgour et al., 1995), can be used to support negotiations in risk management to cope with ambiguity.

5.2.3 Uncertainty about probabilities

Assessing risk involves measuring the likelihood of a hazard or initiating event and tracing the propagation of uncertainty through a system to the consequences. Some events can be said to be more nearly certain than others which allows a DM to ascribe a measure of likelihood (probability) to an event (Halpern, 2005). Kaplan and Garrick (1981) define probability as "a numerical measure of a state of knowledge, a degree of belief, [or] a state of confidence." The subjective state of knowledge, belief and confidence can be mapped to a measuring scale. Calibration of the scale can be done in a number of ways, for example, using frequency (most commonly used and often equated with probability), Bayesian probability, Dempster-Shafer belief functions (Shafer, 1976), possibility rankings and plausibility measures (Halpern, 2005), fuzzy sets (Zadeh, 1973), grey sets (Deng, 1989; Liu and Lin, 2010), and rough sets (Greco et al., 2001). However, extreme events are defined by very low probabilities which lack reliability. Unreliability of data may lead to arguments about the uncertainty in the measurement of probability when multiple participants are involved and interests vary. This is characteristic of extreme events because they affect a high number of participants and data are often not available. Adaptive active learning, based on adaptive management first introduced by Holling (1978) and Walters (1986), is a strategy to cope with uncertainty. It is proposed that with system models and GMCR, participants can experiment with different risk management solutions under different scenarios to identify which solutions work best under what conditions.

5.3 Responsible management of extreme risks

In light of the issues of complexity, ambiguity and uncertainty of extreme risks, a SoS engineering methodology is proposed as a tool to advance the responsible management of extreme risks. In particular, the strategic considerations of multiple participants are integrated into the analysis and management of the risk of extreme events in a SoS. First, catastrophic

SoS failure will be defined. Then, the proposed SoS engineering methodology is outlined for risk analysis to improve management of risk of an extreme event in a SoS.

5.3.1 Catastrophic system of systems failure

In general, all systems consist of interacting components and their interfaces. Based on the characteristics proposed by Maier (1998), Sage and Cuppan (2001) and Sage and Biemer (2007), listed in Table 5.1, (large-scale) systems can be classified into the following two categories: 1) system of sub-systems (or complicated systems), and 2) system of systems (or complex systems). Examples of the former are an Airbus A380 airplane and the Bell telephone network, whereas cited examples of the latter are the Internet (Maier, 1998), healthcare services (Wickramasinghe et al., 2007; Tien and Goldschmidt-Clermont, 2009) and open source software projects (Cowling and Cloutier, 2009). Based on the characteristics listed in Table 5.1, a SoS is different from a system of sub-systems in that sub-systems in a system do not have a function or control in and of themselves independent from the system but only serve a function or is controlled within the context of a system, whereas a system in a SoS has independent function and control in the SoS. In this way, a system in a SoS can exist independently of the SoS, however, a sub-system of a system does not serve any purpose outside of the system.

Of particular interest is that the system architectures differ in terms of robustness against accidental and deliberate attack (Maier, 1998). The particular interest of this work is in the type of attacks that would be considered events of catastrophic consequence. As popular media often imagines, extreme events are “doomsday” scenarios of total system collapses. Therefore, the nature of the risk of system collapse (failure beyond recovery) is considered in a system of sub-systems versus in a SoS. Interfaces between sub-systems are generally well-defined and fixed, hence one focuses on component failure as the cause of system collapse in a system of sub-systems. On the other hand, in a SoS, interfaces between independently functioning and controlled systems are fluid and negotiable, therefore the focus is on interface failure as a cause of system collapse in a SoS.

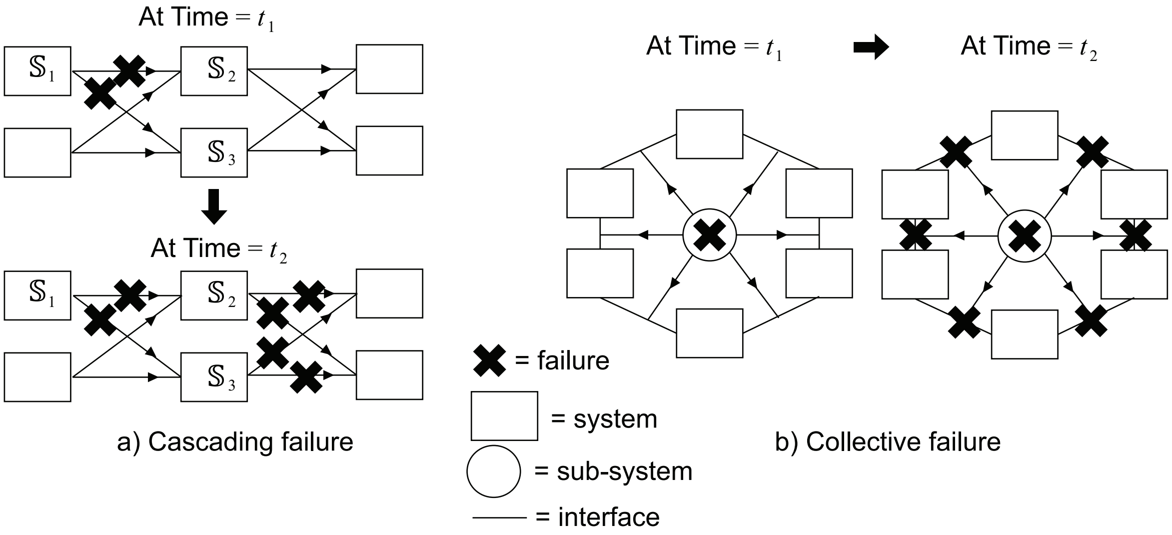
Table 5.1: System of sub-systems versus system of systems characteristics.

	System of sub-systems (Complicated Systems)	**System of systems (Complex Systems)**
Necessary System Architecture	*Operational Dependence of Components:* components cannot function as intended if they are disconnected from the system. *Centralized Control of Components:* components do not make decisions for themselves.	*Operational Independence of Components:* components can perform tasks without any connection to other components. *Managerial Independence of Components:* components are self-governed to a degree. *Directed:* hierarchy, leader sets goals. *Collaborative:* teams, group decides goals. *Virtual:* "flat world", individuals negotiate goals.
Generally follows from System Architecture, but not necessarily	*Localized Distribution*: components are physically "close" to each other. *(Predictable) Emergent Behaviour:* as per requirements, the system achieves intended goals that components cannot accomplish separately. *End-Product Development:* *Fixed Arrangement*: the system maintains the same structure, processes, and purposes. *Optimized*: the system functions best within a specified range of operating conditions.	*Geographic Distribution:* components are physically "far" from each other. *(Unexpected) Emergent Behaviour:* the system performs functions that components cannot do alone and carries out purposes that were not necessarily its original goals. *Evolutionary Development*: *Self-Organization*: components and interfaces can be added, removed and modified, thereby altering the system's structure, processes, and purposes. *Adaptation*: the system can adjust to changing operating conditions.

For a system of sub-systems, it is reasonable to say that the consequence of a component failure is related to its criticality, which is defined as the contribution level to the functioning of the system or the impact level on the system from its disruption or destruction (Theoharidou et al., 2010). Theoharidou et al. (2010) propose an interdependencies-based methodology as a way to measure criticality. The risk of system collapse depends on the probability of a critical component's failure, in which critical implies a criticality above a certain threshold. Following this, redundancy or timely backup of critical components is thus a main determinant of robustness or resiliency, respectively, which is often challenged by a system of sub-systems' tendency toward specialization which removes redundancies to improve efficiency (Maier, 1998). Reliability engineering and preventative maintenance are well-established fields for managing operational risk in a system of sub-systems.

On the other hand, a SoS is inherently redundant as a requirement of operational independence of its component systems (Maier, 1998). Instead of reliability of critical components, the dominant concern in a SoS lies in the reliability and stability of interfaces between systems. A SoS ceases to be a system if component systems cannot or choose not to interact. As an example, component systems may not be able to coordinate as a system if communication links are unreliable, as in the Two Generals' Problem (Akkoyunlu et al., 1975) and Byzantine Generals Problem (Lamport et al., 1982). Alternatively, they may choose not to cooperate if relationships between them are unstable, as in the games of Prisoner's Dilemma and Chicken (Rapoport and Chammah, 1965, 1966; Axelrod, 1984; Brams, 1985). Given a SoS with a large number of systems, a small number of failed interfaces may not seem significant assuming the same logic that a small number of failed components is not an issue because of built-in redundancies. This would be true if the effects of a failed interface were isolated. In light of cascading failures through networks demonstrated by power grids and financial systems however, effects are often not isolated, which makes the whole network vulnerable to the propagation of failure from one part to other parts, eventually resulting in collapse. A SoS, to the extent that it is a network, also suffers from this potentially fatal flaw. Therefore, the capability of component systems to coordinate or cooperate in spite of interfacing issues and the ability of the SoS to isolate the effects of and repair interface failures are the main determinants of robustness and resilience, respectively.

Actually, catastrophic SoS failure can be of two types: 1) cascading failure, and 2) collective failure. Cascading failure at the level of interactions involves the propagation of at least one type of interface failure, for example, potential transmission of wrong information, overloading of transmission capacity, or disincentives to engage. Causes of interface failure may also include, but are not limited to, tight couplings, chain reactions, and positive feedback paths through unknown and unintended interfaces. This type of SoS collapse is illustrated in Figure 5.2a. At time t_1, system $\mathbb{S}_1$ transmits a message in error to downstream systems $\mathbb{S}_2$and $\mathbb{S}_3$. At the next time step t_2, the error propagates to all other downstream



a) Cascading failure

b) Collective failure

Figure 5.2: Catastrophic system of systems failures.

systems, which effectively causes the SoS to fail although individual systems continue to function. Alternatively, it is conceivable that the source of a catastrophic SoS failure could be the malfunction of an underlying critical sub-system that enables information, energy and mass flows between systems. Failure of this critical sub-system would result in the collective failure of interfaces among multiple systems, illustrated in Figure 5.2b. At time t_1, the critical sub-system fails. In the next time step t_2, this failure emanates to all connections between systems that depend on this sub-system, effectively reducing the SoS to a collection of systems. These critical sub-systems are known as “critical infrastructure”, which in their own right could be classified as a SoS from a perspective within the infrastructure system, but from the higher-level viewpoint their criticality implies a non-redundancy that infers them to be sub-systems of a higher-level SoS. These two types of failures are what is meant by catastrophic SoS failure, which as an extreme event is fraught with the issues of lacking knowledge of the system, consequences, and probabilities in order to assess and manage its risk. Thus, a SoS engineering methodology for navigating through the complexity, ambiguity and uncertainty of the risk of catastrophic SoS failure is proposed below.

5.3.2 System of systems engineering methodology for risk analysis

SoS engineering is about leveraging interfaces among systems to achieve goals that are negotiated and evolve over time as the states and relationships among individual systems change. Having goals be negotiated and evolve implies that the process has to consider strategic interactions among multiple participants dynamically. Although competing and conflicting objectives of multiple participants have been considered in risk analysis (Haimes, 2009a; Yan and Haimes, 2011a, 2011b), strategic interactions of moves and countermoves that can change the dynamics of the risk situation is often not. As a result, risk is a dynamic measure that depends, not only on changing surroundings, but also on changing perceptions of multiple participants based on how they set their systems' boundaries, what they consider to be important according to their values, and what strategies they decide to pursue over time unilaterally or, perhaps under the right conditions, multilaterally. The output measure of risk need not necessarily be agreed on and as a result participants may adopt different risk management strategies for their respective systems. Consequently, the management of risk in a SoS is an outcome that results from strategic interactions among participants, who act autonomously but whose intentions, decisions and actions can affect other participants in other systems.

The proposed methodology first focuses on developing system models among participants to communicate different perspectives in a common framework, and second, concentrates on developing adaptive and robust solutions that address the risk of catastrophic SoS failure. Essentially, the process is divided into two phases. The first phase is integrative in that a risk analyst attempts to translate individual system perspectives and risk perceptions held by participants into a common modeling framework to generate pluralistic system models. The second phase is adaptive in that a risk analyst attempts to iteratively find adaptive and robust resolutions that address the risk of catastrophic SoS failure, defined as the cascading or collective failure of interfaces among systems.

Phase 1: Risk perception - understanding the problem

The objective of this phase is to develop pluralistic understanding of the risk of a catastrophic SoS failure. The process begins with a risk problem statement that names the SoS and the participants. This statement is a living statement that can be continually edited or updated. Each participant has his or her own view of the SoS (perspective), value system (interests), and area of influence (risk management strategies). A participant's risk perception depends on these three things and on what the focal participant knows of the risk management strategies of other participants and their preferences over the possible risk management outcomes. A system model for each participant explicitly structures each participant's perspective.

Figure 5.3 illustrates the template of a general model structure to elicit a participant's risk perception which is the totality of hazards, consequences, system states, risk management strategies, and the relationships among them. Since risk must always be considered within a decision theory context (Kaplan and Garrick, 1981), the first step is to list the consequences that matter to the focal participant based on the participant's objectives. A value-focused thinking approach (Keeney, 1992) can be utilized to elicit attributes to measure the achievement of objectives. These attributes are proxies for measuring consequences. Then working backwards from the consequences, the second step is to identify hazards and threats that present the potential to lead to negative consequences. Attention should be paid to identify emergent threats and conditions which would influence the risk perception. Karvetski et al. (2009) developed a methodology to capture how participants, under different emergent conditions, may alter their tradeoffs. As a result, participants' preferences over risk management alternatives would change as the inter-criteria weights modulate to represent different tradeoff judgments, which provide important information about preferences for Phase 2 of the proposed methodology. Next, the third step is to brainstorm actions that the focal participant and others can take to influence the system. Finally, the fourth step is to delineate factors that specify the response of the system and establish a functional relationship between hazards/threats, strategies, system factors, and consequences. This template is a learning tool which means that participants' specific models will need to be modified as new information becomes available. In particular, effective risk management options may not yet be known until a functional relationship in the system is discovered. As the model is based on a participant's perception, knowledge to create the model will be inherently incomplete and subjective, but nonetheless sufficient.

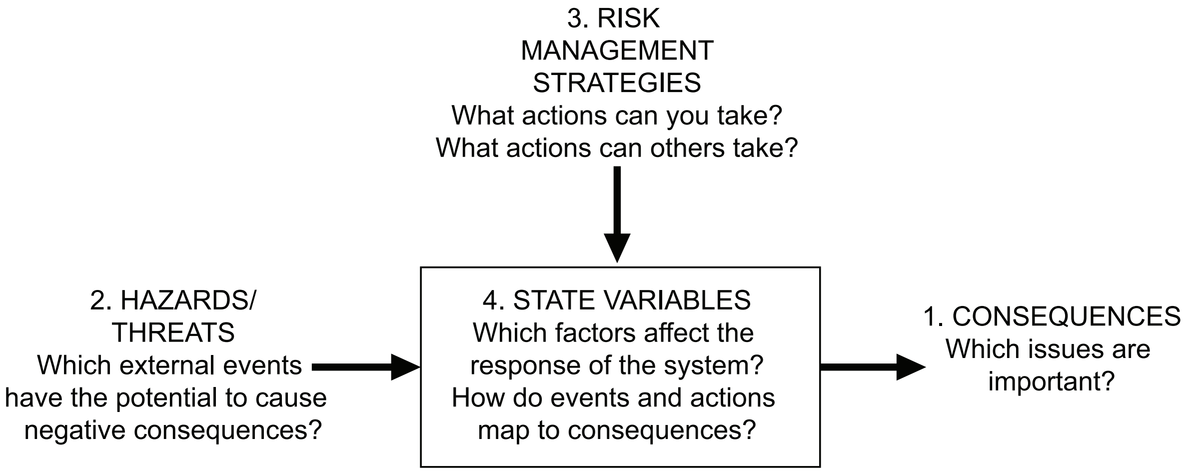


Figure 5.3: General system model structure to elicit a participant's risk perception.

There are two goals in this modeling exercise. The first goal is to gain clarity on the problem from different perspectives so that risk management options become more obvious. The second goal is to gain insights on how different risk management outcomes (consisting of the possible actions of all participants) influence the severity and probability of consequences as seen through a participant's perspective. For the methodology presented herein, a qualitative model will suffice as a logical basis to specify preferences over risk management outcomes. The models may at a later time be quantified with statistics calculated from empirical data and using a state-space representation as proposed by Haimes (2011), or with specific risk quantification methods developed for the specific problem, as in the case for maritime transportation risk (Gramling et al., 1998; Fowler and Sorgard, 2000; Martins and Maturana, 2010). Moreover, where available such as for the extreme threat of terrorism (Clauset et al., 2007), scaling laws may be invoked as input into the model. Risk perceptions feed into how participants collectively govern risk. From perceiving risk of SoS failure to managing the risk, a GMCR framework is presented in the next step to develop an understanding of the collective behaviour of participants that results from strategic interactions to manage risk.

Phase 2: Risk management - finding a resolution

A resolution in the context of risk constitutes a risk management outcome. A risk management *outcome* consists of the risk management strategies of all participants. A risk management *strategy* for a participant consists of risk management options that the participant intends to take. A risk management *option* is an action that can be taken to prevent an event from happening, reduce probability or severity of an event, or respond to an event. Different participants may prefer some outcomes over others based on whether or not perceived risks decrease and the allocation of benefits and/or costs. Conflict arises when actions of one or more participants increase risks or unfairly distributes benefits or costs to participants.

Risk management should consider strategic interactions among participants when there is conflict among participants, which tends to happen in situations with multiple participants. Strategic interactions affect the risk management outcome which in turn modifies the perceived risk level for each participant. Using the knowledge of how different risk management outcomes influence a participant's perceived risks, participants enter into a game-like arena in which the object of the game is to reach a more preferred outcome from the status quo, for all participants (assuming that one exists). Participants are opponents in the sense that actions of one participant can increase the risks or costs to other participants. When effects of actions on others are unintentional, participants may communicate directly to negotiate resolutions; whereas if they are intentional (as in armed conflict), participants may not desire to communicate directly or negotiate. A strategic analysis of the game provides insight on how to find a resolution to the given risk problem that is better than the status quo.

Referring back to the risk problem statement, a resolution statement is needed to specify criteria of a desired outcome from a SoS perspective that might resolve the corresponding problem. Likewise, the resolution statement is a living statement that can be edited and updated. Comparison of the status quo with the resolution statement signals whether further risk management action is required. The objective of this phase is to assess whether participants can reach the desired resolution and to gain insight on how to reach the desired outcome.

To identify the likely risk management outcome, or likely resolution to the risk problem, strategic interactions in the management of risk are analyzed using the framework of GMCR (Fang et al., 1993; Hipel and Fang, 2005; Hipel et al., 2011c). GMCR is a systems methodology for modeling and analyzing conflict among multiple participants. The modeling steps are as follows: 1) identify participants, 2) identify options for each participant (a strategy is the combination of options that a participant can pursue), 3) remove infeasible outcomes (an outcome is a scenario of risk management strategies represented as an aggregation of participants' selected strategies), and 4) specify preferences over all of the feasible outcomes for each participant.

Risk will affect a participant's preferences based on the perception and value system of the participant used to rank possible risk management outcomes. For example, a risk-averse value system would rank outcomes that are perceived to lead to high risk as less preferred than outcomes that are perceived to lead to low risk. As mentioned above, participants' preference may change according to the scenario derived from emergent threats and conditions. Information from models of risk perceptions developed in Phase 1 is used to delineate participants' preferences over possible outcomes. With this information, a variety of multiple criteria decision analysis methods, such as multi-attribute utility theory (Keeney and Raiffa, 1976, 1993) and the analytic hierarchy process (Saaty, 1980), can be invoked to elicit preferences. Preferences need not be certain or crisp as there are also techniques to handle preference uncertainty (Li et al., 2004) and fuzzy preferences (Hipel et al., 2011a) in the GMCR framework.

Although, participants themselves may keep their interests hidden from other participants, an analyst can specify each participant's preferences based on available information from participants or other resources. An inconsistency between a participant's actions and the predicted outcome of the GMCR model indicates the possibility of a hidden interest that was not considered in the original model and can be appropriately updated in subsequent modeling and analyses to ascertain strategic impacts. As hidden interests may be present during negotiations that involve a complex SoS, it is important to realize that the GMCR results may be limited. However, most models are restricted in some way by the unknown. It is important to recall that an adaptive management approach uses models in conjunction with hypothesis testing methods, such as experimentation and sensitivity analysis, to evolve solutions. Since it is impossible to know of a hidden interest for certain until it is revealed, the best that an analyst and participants can do to assess the validity of the

GMCR results is to test them with present knowledge and compare them to a past conflict for which the actual resolution is known. An analyst may also consider experimenting with different preferences in order to explore a number of potential evolutionary paths to different solutions.

With the specification of participants, their options and preferences over outcomes, stability analyses can be run to determine equilibria based on different hypotheses of human behaviour in decision making known as solution concepts (Fang et al., 1993, 2003a, 2003b). In this way, GMCR takes into account strategic interactions that result in emergent collective behaviour. The solution concepts used in a stability analysis find equilibrium, an emergent collective phenomenon based on the strategic interactions among DMs. By analyzing strategic interactions with GMCR, complexity that arises from the emergent collective behaviour of participants is addressed in the risk governance process. Risk governance is defined as the totality of risk identification, risk and concern assessments, risk characterization and evaluation, risk management and communication (IRGC, 2005). GMCR II is a decision support system that automates the analysis (Fang et al., 2003a, 2003b). Analysts can create multiple conflict models and obtain results quickly to test policy solutions that seek to change participants' preferences in order to reach the desired risk management outcome (Hipel et al., 2009a; Bristow et al., 2012a, 2012b, 2013a, 2013b).

From an adaptive management perspective, Walters (1986) wisely states that management involves a continual learning process and that there is no recipe to follow to catch all scenarios that may be important to all of the participants. In fact, there should never be a clear ending or final state to adaptive management because it is an ongoing process. The general approach described by Holling (1978) and Walters (1986) is a workshop process which brings together disciplinary experts, managers, DMs and modelers to build models, develop and test scenarios, and explore alternative policies. The process is an interactive search for adaptive and robust solutions. In the next section, an adaptive management process is adopted in the case study to demonstrate the effective use of system models with GMCR models for risk analysis and management in a SoS.

5.4 Case study: global maritime critical infrastructure

For this case study, global maritime transportation is considered as a SoS. Mansouri et al. (2009) provide a descriptive account of the maritime transportation SoS and propose a SoS management framework to govern management processes. Ships, ports, intermodal connects, waterways and users are considered as "agents" of a maritime transportation SoS that are autonomous operational systems. The case study here differs from that of Mansouri et al. (2009) by focusing on a specific region, namely the Straits of Malacca and Singapore located in Southeast Asia, as shown in Figure 5.4, as a key interface within the global maritime transportation SoS. Moreover, this case study focuses on the management of the risk of an extreme event in which the strategic interactions of multiple participants are considered rather than general management of the global maritime SoS.

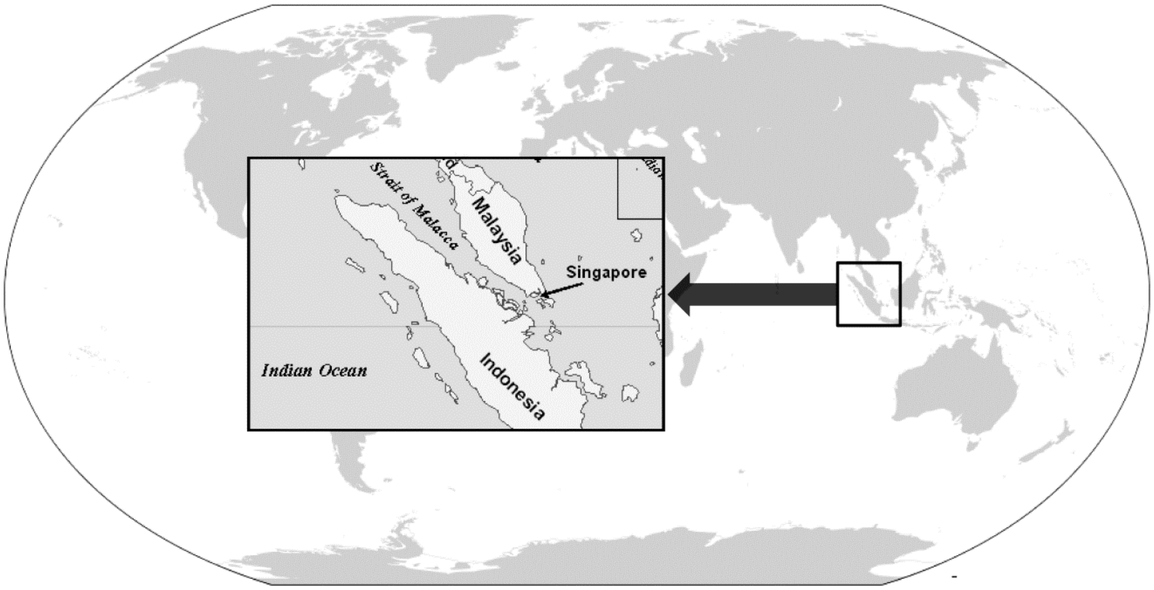


Figure 5.4: The Straits of Malacca and Singapore are bordered by Malaysia, Indonesia and Singapore.

5.4.1 Expert workshops and problem background

Three expert workshops on the Risk Governance of Maritime Global Critical Infrastructure focusing on the Straits of Malacca and Singapore exposed to extreme hazards were hosted by the Disaster Prevention Research Institute at Kyoto University (DPRI-KU), the Centre for Maritime Studies at the National University of Singapore and the International Risk Governance Council (IRGC) in June 2009, April 2010 and November 2010. These workshops provided the opportunity to interact with participants from government, industry, international organizations and research institutions related to maritime systems, and to gain insights on their perspectives of the Straits of Malacca and Singapore and the perceptions of risk of extreme events in terms of scenarios, consequences and probabilities. Outcomes of the workshop are published in a peer-reviewed report (IRGC, 2011). These expert meetings served a similar purpose as the first workshop recommended by Holling (1978) to establish momentum, however differed in that the ultimate goal of the workshops was to take stock of risk governance deficits. Nonetheless, it is a good start towards an adaptive management process.

Among the major concerns expressed by the workshop participants was a "free-rider" problem, that is, most of the transiting ships benefit from the navigational infrastructure along the international passage but do not necessarily bear any of the costs for its maintenance and modernization. In addition to infrastructure for navigational safety, there are related concerns on the impact of shipping on biodiversity and the impact to the area of potential ship collisions and malicious attacks on ships in the Straits. Indonesia, Malaysia and Singapore, hereafter referred to as the littoral states, are burdened with the costs of maintaining infrastructure for the safety, security and environmental protection of the Straits. User states have the right to use the Straits for international navigation and cannot be impeded during innocent passage. While Article 43 of the United Nations Convention on the Law of the Sea (UN, 1982) states that "user states and states bordering a strait should by agreement cooperate: (a) in the establishment and maintenance in a strait of necessary navigational and safety aids or other improvements in aid of international navigation; and (b) for the prevention, reduction and control of pollution from ships," only recently has this provision been acted upon for the first time. The "Cooperative Mechanism," which consists of (1) a forum, (2) a fund, and (3) projects, was established to enhance cooperation among the littoral states, user states, shipping organizations and other stakeholders who had an interest in the safety of navigation in the Straits. Ho (2009) attributes the success of the framework to the inclusiveness of different stakeholders outside of governments, the integrity of the management of the funds, and the avoidance of compulsory charges in favor of voluntary contributions. The interest and participation in the Cooperative Mechanism exhibits the value of such a framework, however, challenges still lie ahead in sustaining the contributions to meet the needs of all the stakeholders and in effectively addressing the free-rider problem. Cooperation is needed to address transboundary hazards and threats which, if unchecked in increasingly stressed systems, can materialize into catastrophic consequences.

Risk Problem Statement: The risk problem statement based on the above situation is: How can littoral states, user states, and international shipping organizations effectively manage the risk of catastrophic system collapse of the Straits of Malacca and Singapore? The participants are Singapore, Malaysia, Indonesia, and the user sector which is divided into public participants such as user states and their port authorities and private participants such as international shipping organizations. The SoS is the global maritime transportation network in which the Straits of Malacca and Singapore are a critical interface between ports. Catastrophic SoS failure is defined as when international shipping through the Straits is disrupted.

5.4.2 Perceptions of risks in the Straits of Malacca and Singapore

Each participant has its own perspective which translates to different objectives, concerns and preferences, and thus a different risk perception. Using the system model template in Figure 5.3, participants' models are illustrated in Figure 5.5 and explained below. While high-fidelity detailed quantitative models are desirable, it is useful to start with low-fidelity conceptual models to determine data requirements, the validity of assumptions, costs of development, and an acceptable tradeoff between model complexity and ease of understanding. In addition to these technical issues, participant involvement in the development is a key factor in the creation of useful models according to participants' objectives and concerns. If data are proprietary, commitment by participants to the process would be needed in order to negotiate acceptable data sharing agreements. At this initial stage, models are based on dialogue with representative participants and a review of literature.

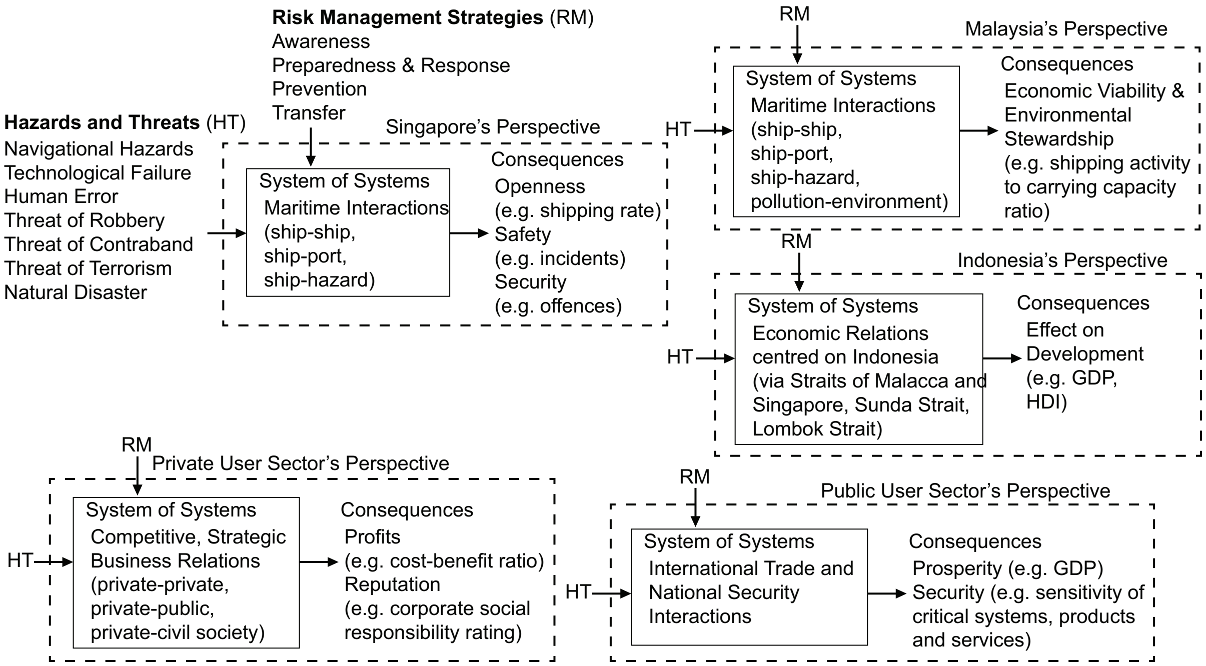


Figure 5.5: Different risk perceptions from multiple participants' perspectives.

Consequences and system perspectives

Singapore is a nation located on an island with very little natural resources but a very spirited capitalist culture balanced by a strong authoritarian government. The port of Singapore is corporatized, but is 100% owned by government (Cullinane et al., 2007). As an international hub for business and industry, the port and the Straits of Malacca and Singapore constitute a "lifeline" for Singapore, which means that Singapore could be fatally affected if open, secure and safe passage through the Straits is compromised. Therefore, the objectives of Singapore are to maintain an acceptable level of openness, security and safety for ships transiting the Straits. Measuring the achievement of these objectives is straightforward. The attribute (Keeney, 1992) for openness is the rate of transiting ships. Safety is measured in terms of the number and severity of ship incidents (e.g. oil spills, hazardous and noxious substances (HNS) incidents, collisions and groundings). Security can be captured in the number and severity of offences, whether attacks on ships or contraband in ports. As such, Singapore focuses on the system of maritime interactions among ships, between ships and ports, and between ships and hazards, which can be described by their states of communication or information exchange and capacity to take actions.

Malaysia utilizes the Malacca Strait for international shipping business as well as for its biodiversity and ecological services, which are assaulted on many fronts by overfishing, mangrove clearing for aquaculture, urban and agricultural waste, and oil spills from ships (Thia-Eng et al., 2000). Malaysia's objectives are environmental stewardship and maximum sustainable economic development. This is not to say that Singapore does not care for the environment, but rather that the livelihoods of a significant portion of Malaysians depend on the natural resources in the Malacca Strait which should factor significantly into Malaysia's decision making. Economic and environmental objectives are sometimes conflicting though tightly interdependent. Due to this interdependency, the notion of ship carrying capacity (Ibrahim and Sh, 2009; MIMA, 2010) has been proposed to determine a limit which would protect the environment at a level that provides for the subsistence of the economy. Essentially, the two objectives are simultaneously achieved when the actual activity is at the carrying capacity. Malaysia focuses on the same system of maritime interactions that Singapore does but augmented with environmental concerns. The difference in consequences illustrates a subtle key difference in the risk perceptions of Malaysia and Singapore. Although Malaysia and Singapore would both agree that the environment is protected as long as the risk of ships collisions and oil spills are managed, Malaysia currently argues for a limit on maritime traffic (Hock, 2008), which runs counter to Singapore's ideal of openness.

Indonesia's attention is spread over a broader scale geographically and socioeconomically. Indonesia has many times more coastline (54,716 km) than Malaysia (4,675 km) and Singapore (193 km) (CIA, 2013). The next best alternative routes to the Straits of Malacca and Singapore are the Sunda and Lombok straits, both located exclusively in Indonesia's territorial waters. Indonesia, more than Malaysia and Singapore, is prone to extreme natural disasters including tsunamis, earthquakes, volcanic eruptions, flooding, drought, and forest fires. Indonesia is also dealing with socioeconomic challenges of illegal logging and land clearing, robbery at sea and terrorism on land, which have transboundary effects on the safety and security of the region. Indonesia's objectives are to develop its own capacities and perhaps to leverage relationships to elevate itself to the development status of its closest neighbours. In Indonesia's case, attributes are comparative national performance metrics such as Gross Domestic Product (GDP) and the Human Development Index (HDI). As a result, Indonesia considers not just the Straits of Malacca and Singapore, but also factors the development of its other waterways as competitive gateways into its decision making. This broader perspective challenges Malaysia and Singapore to consider the influence of Indonesia's actions in increasing or decreasing transboundary threats such as robbery and terrorism.

All three littoral states value their sovereignty, with Malaysia and Indonesia being more protective, and thus skeptical of foreign agents in their territorial waters, than Singapore. As an international passage, however, risk in the Straits affects and is affected by users. From the perspective of the private user sector, shipping organizations are concerned about the direct impact on their ships that use the Straits and the effects on their business including its profits and reputation. Consequences to a shipping organization can be measured in terms of financial cost-to-benefit ratio as well as rating of corporate social responsibility. Its SoS perspective consists of the competitive and strategic relations between itself and other entities. From the public domain perspective, user states are concerned about the indirect impacts on their national economy and security. Consequences to user states include decreases or increases to measures of prosperity (GDP) as well as national security in terms of sensitivity of critical systems, products and services. International trade and its relation to national security constitute the SoS perspective of a state.

Hazards and threats

Initially, it was hypothesized at the first expert workshop that the Straits could be exposed to extreme natural hazards. The geography of the Straits shelters the waterway from natural disasters, such as the Asian Tsunami in 2004. However, efforts have been made to simulate impacts of a future Andaman tsunami into the Strait of Malacca (Koh et al., 2009). Workshop participants shared their concerns about human activities in and around the Straits that create hazardous conditions. Increasing usage of information and communication technologies raises concern about cyber attack or technological failure. Increasing traffic flow and ship sizes leads to concerns about navigational hazards such as reduced visibility from haze, ship wrecks and shoals, cross-traffic and transit-traffic interactions, and wrecked navigational aids. Any ship incident presents a threat of oil spill. Increasing transport of HNS also heightens the threat of HNS incidents at sea or in port. Threats to security include intentions by perpetrators to commit robbery, acts of terrorism, or smuggling. The list of hazards and threats can include any of these situations as initiating events, including an unexpected natural disaster regardless of whether the participants consider them as highly unlikely. In fact, creativity in imagining events is needed to explore scenarios that would otherwise be surprising. By assuming that anything is possible, risk analysts use the above models to concentrate on risk prevention, mitigation and adaptive management more so than on estimation and prediction.

Risk management strategies

Risk management strategies fall into the general categories of awareness, preparedness and response, prevention, and transfer. In conventional risk analysis, each participant would decide individually whether or not risk is high enough to warrant devoting resources to risk management with the expectation of reducing risk to a desired level. However, in a SoS, interfaces can allow the inadvertent increase of risk to others. For example, persons who commit crimes in Malaysian or Singaporean waters can easily escape into Indonesian waters (Beckman, 2002). Without the capacity or motivation to capture these international criminals, Indonesia unintentionally increases Malaysia’s and Singapore’s risk of offences in their waters. Conversely, risk in Malaysia and Singapore’s waters would be reduced if Indonesian waters were no longer a refuge for offenders. Of course, it is not intentional on Indonesia’s part to increase the risk in the Straits of Malacca and Singapore, but an understandable outcome because of Indonesia’s geography and current stage of development. Effective risk management in a SoS requires that all participants work together, which necessitates consideration of others’ interests to generate motivation to do so. By the old adage that “a chain is only as strong as its weakest link,” individual risk management strategies would be fruitless without such cooperation. Therefore, participants in a SoS would decide whether to devote resources to risk management if there is strategic rationale for everyone to cooperate and if there is reasonable expectation that collective action would reduce risk to a desired level.

Risk Resolution Statement: Recognizing that cooperation is needed but that a credible agreement requires a strategic rationale to cooperate, the desired risk management resolution of the risk governance process is a strategically stable cooperative outcome.

The next subsection demonstrates the use of a GMCR framework in conjunction with the risk perception models to analyze strategic interactions among the participants and as a potential testing platform to evaluate potential solutions to achieve the desired risk management outcome.

5.4.3 Management of risks in the Straits of Malacca and Singapore

Before participants engage in detailed coordinated implementation of risk management actions, participants need to rationalize the effort. Consider the problem of a lack of voluntary contributions from users of the Straits of Malacca and Singapore to the Aids to Navigation Fund, which was established in May 2008. Based on an assessment survey of critical aids to navigation in the Straits in 2008, the estimated annual average cost is 5.8 million USD to maintain and modernize the aids (TTEG, 2010). Contributions from users over the period of May 2008 to October 2010 has summed to 8.10 million USD (TTEG, 2010), which falls short on average per year by 40 percent of the estimated annual cost. Solutions are needed to decrease this gap. If unaddressed, the deterioration of navigational infrastructure would likely be cited as a major factor out of many that could lead to a catastrophic ship collision in the Straits. The problem is a characteristic free-rider problem, which is exemplary of risk management problems in which risks are externalities to beneficiaries of an open resource such as in the case of the Straits of Malacca and Singapore.

GMCR models of strategic interactions connected to risk perceptions

For explanatory purposes, an initial GMCR model to understand the free-rider problem was constructed to serve as a basis for discussion among workshop participants. The model considers five participants, who represent Singapore, Malaysia, Indonesia, the public user sector and the private user sector. For simplicity, each participant has the option to contribute to a common pool fund for the maintenance and modernization of navigational aids in the Straits of Malacca and Singapore, i.e. the Aids to Navigation Fund. Whether or not to contribute to the fund is a risk management decision. Therefore, each has two possible strategies, to contribute or not to contribute. The total number of possible outcomes, given five participants with one option each, is $2^5 = 32$. Each outcome is labeled with a number from 1 to 32 and represents an aggregation of participants' strategies, where a "✓" means a participant decides to contribute and a "✖" means a participant decides not to contribute. For example, outcome 16 is when participants A, B, and C contribute (✓), but participants D and E do not (✖), as shown in Table 5.2.

Table 5.2: Feasible outcomes for the GMCR model of the free-rider problem.

Participants	**Options**	**Outcomes**														
		1	2	3	4	5	6	…	16	…	27	28	29	30	31	32
A. Singapore	Contribute?	✖	✓	✖	✓	✖	✓	…	✓	…	✖	✓	✖	✓	✖	✓
B. Malaysia	Contribute?	✖	✖	✓	✓	✖	✖	…	✓	…	✓	✓	✖	✖	✓	✓
C. Indonesia	Contribute?	✖	✖	✖	✖	✓	✓	…	✓	…	✖	✖	✓	✓	✓	✓
D. Public Users	Contribute?	✖	✖	✖	✖	✖	✖	…	✖	…	✓	✓	✓	✓	✓	✓
E. Private Users	Contribute?	✖	✖	✖	✖	✖	✖	…	✖	…	✓	✓	✓	✓	✓	✓

The free-rider problem emerges as a result of the preferences of participants. Free-riding refers to the fact that users of the Straits are able to traverse them without having to pay the costs of maintaining or upgrading the infrastructure that keeps and enhances the safety and security of the Straits. However, without sufficient funds, the infrastructure would eventually deteriorate leading to a worse condition for all users. The problem is akin to the well-known phenomenon of the Tragedy of the Commons, first described by Hardin (1968) as a situation in which multiple herders, acting independently and rationally, deplete a common parcel of land through over grazing even though it is not in anyone's long-term interest for this to occur. It is also an extension of the well-studied Prisoner's Dilemma, in which each player must decide whether or not to cooperate with the other. The preference of each player acting on his or her own in the short term is not to cooperate with the other even though it would be better in the long-term to cooperate.

To demonstrate the logic behind the derivation of the preferences for the 5-player free-rider problem, rules are derived from the preference structure for the 2-player Prisoner's

Dilemma, and extended to a 3-player Tragedy of the Commons with some assumptions, then applied with assumptions to the 5-player model. The outcomes and preferences in Prisoner's Dilemma for each prisoner are listed in Table 5.3 and illustrated in Figure 5.6. In the graphs in Figure 5.6, the nodes represent outcomes while the arcs stand for the unilateral movements of the focal prisoner. The left-most node is the least preferred outcome whereas the right-most node is the most preferred.

Table 5.3: Specification of 2-player Prisoner's Dilemma outcomes and preferences.

Players	**Options**	**Outcomes**				**Preferences**
		1	2	3	4	
Prisoner A	Cooperate?	×	✓	×	✓	$2 \prec 1 \prec 4 \prec 3$
Prisoner B	Cooperate?	×	×	✓	✓	$3 \prec 1 \prec 4 \prec 2$

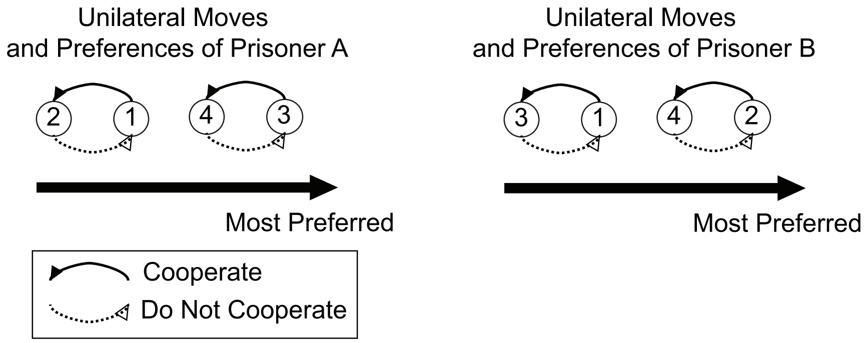


Figure 5.6: Graphical form of Prisoner's Dilemma.

Specification of the preferences for a Tragedy of the Commons game consisting of three players mirrors Prisoner's Dilemma in that a herder prefers most that others restrain from grazing his herds while he does not and prefers least to be the only one to restrain, just as a prisoner prefers most that the other cooperates while he does not and prefers least to be the only one to cooperate. The ordering of the rest of the outcomes requires some assumptions. First, it is assumed that more restraint is better than less. For example, everybody restraining is generally more preferred than only one other restraining. Second, it is assumed that a herder is indifferent to other herders. That is, to herder A, it does not matter if only herder B or only herder C restrains, as both outcomes (outcomes 3 and 5) are equally preferred. The resulting preferences are listed in Table 5.4 and illustrated in Figure 5.7.

Table 5.4: Specification of 3-player Tragedy of the Commons outcomes and preferences.

Players	Options	Outcomes								Preferences
		1	2	3	4	5	6	7	8	
Herder A	Restrain?	✗	✓	✗	✓	✗	✓	✗	✓	$2 \prec 1 \prec 4 \sim 6 \prec 3 \sim 5 \prec 8 \prec 7$
Herder B	Restrain?	✗	✗	✓	✓	✗	✗	✓	✓	$3 \prec 1 \prec 4 \sim 7 \prec 2 \sim 5 \prec 8 \prec 6$
Herder C	Restrain?	✗	✗	✗	✗	✓	✓	✓	✓	$5 \prec 1 \prec 6 \sim 7 \prec 2 \sim 3 \prec 8 \prec 4$

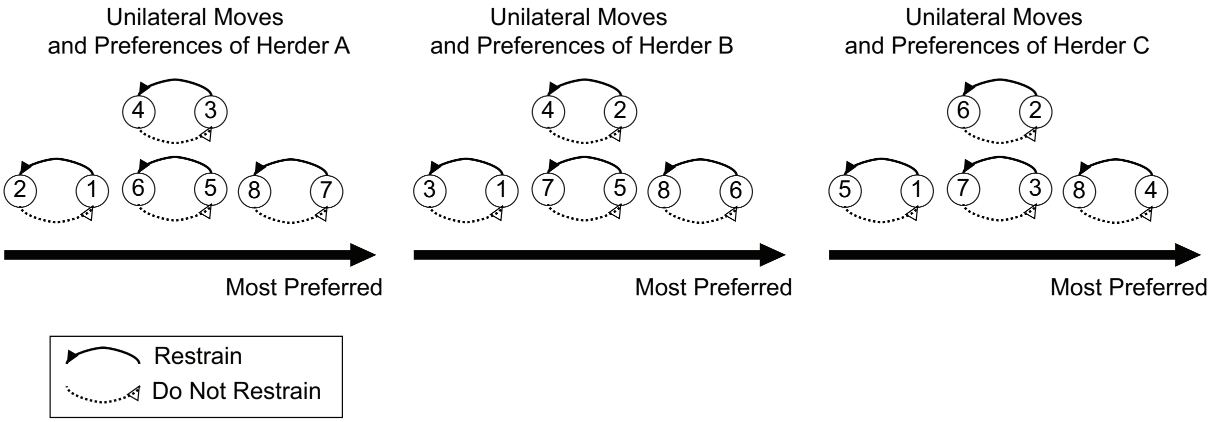


Figure 5.7: Graphical form of 3-player Tragedy of the Commons.

Extending the preference structure to the 5-player game in Table 5.2 can be done by following these general rules: 1) each participant prefers not to contribute, and 2) outcomes in which more participants contribute are more preferred. As an example, the preferences of participant B: Malaysia, assuming a free-rider value system, is shown in graphical form in Figure 5.8a. It would also be possible to modify the preferences according to different tradeoffs between the cost of contributing and benefit of risk management efforts. Perhaps the benefit exceeds the cost only if a certain threshold number of participants contribute. To reflect such a cost-benefit tradeoff, the following additional rules would replace the first rule: 1a) each participant prefers to contribute only if more than x% of other participants contribute; 1b) each participant prefers to not contribute if less than x% of other participants contribute. A formalized modified MCDA method (Ke et al., 2007, 2012a, 2012b) can also be used to obtain preferences for each participant according to the relative influencing power of other participants and the relative desirability of options according to a participant's objectives.

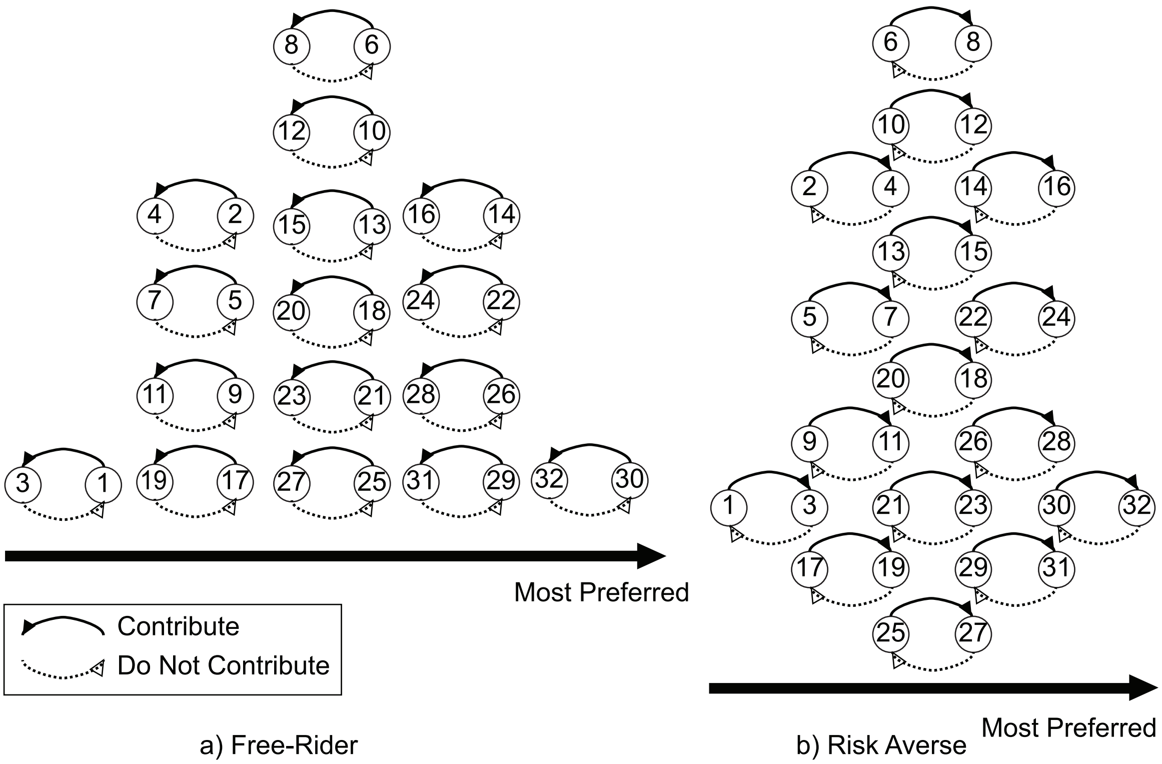


Figure 5.8: Unilateral moves and preferences of participant B: Malaysia.

The participants, their options and their ordinal preferences are the only information needed to specify a complete GMCR model. With this information, stability analyses can be run using different solution concepts (Fang et al., 1993), implemented in GMCR II (Fang et al., 2003a, 2003b), to obtain the likely outcome. If a participant's objectives are gains in the short-term, then Nash stable strategies would most likely be selected. If a participant's objectives are to avoid losses in the long-term, then strategies that prevent others from moving to a worse outcome for the participant are likely chosen. The results of the stability analyses for the 2-player, 3-player and 5-player games are listed in Table 5.5, from which a pattern emerges. Any outcome in which only one player cooperates is unstable. An unstable outcome by all stability definitions means that a more preferred outcome is expected to result from changing one's strategy regardless of the level of foresight. The outcome in which no one cooperates is Nash stable, and also stable for all other solution concepts. Nash stable means that if all participants have low foresight, then no cooperation would be the likely outcome. Participants would only be interested in short-term gains. All other outcomes are unstable under Nash equilibrium, but stable for concepts that require players to have foresight, that is to anticipate counter-moves by other players. In other words, DMs need to be strategic for the cooperative resolution to be stable. Participants' objectives need to consider more than just short-term gains.

Table 5.5: Comparison of stability results of different games.

Games	**Number of Players**	**Unstable Outcomes**	**Stable**	
			Nash Stable	**Unstable under Nash equilibrium**
Prisoner's Dilemma	2	{2, 3}: only one player cooperates	{1}: no one cooperates	{4}: both cooperate
Tragedy of the Commons	3	{2, 3, 5}: only one player restrains	{1}: no one restrains	{4, 6, 7, 8}: more than one restrains
	5	any outcome in which only one player contributes	no one contributes	any outcome in which more than one player contributes
Littoral states are strategic about risk	5	{1, 8, 17}: no one contributes, or only one of the public and private users contributes	{8}:all littoral states contribute but the private and public user sectors do not	{32}: all contribute {…}: all other outcomes

If participants are not strategic, then the likely risk management outcome would be that no one contributes. What would this outcome mean to participants' risks based on their risk perceptions depicted in Figure 5.5? From Singapore's perspective, the system of ship interactions would become extremely vulnerable to ship collisions thereby lowering safety. Similarly, Malaysia would perceive a decrease in carrying capacity. Therefore, increases in traffic would put more stress on the environment. Indonesia, although it is also concerned with its other waterways, is equally responsible for the safety in the Straits and would also consider deterioration of navigational infrastructure negatively with respect to its development goals. Indeed, the littoral states do not hold the same preferences as assumed by players in a Tragedy of the Commons game. Their actions of investing in the safety of the

Straits affirm that their risk perceptions lead them to prefer a "contribution" strategy on their own part over a "no contribution" strategy. Therefore, in considering their risk perception, the game is changed such that 1) Singapore, Malaysia, and Indonesia prefer to contribute, and 2) outcomes in which more participants contribute are more preferred. As an example, the actual preferences of participant B: Malaysia, assuming a risk-averse value system, are shown in graphical form in Figure 5.8b. Their risk perceptions change their preferences, which in turn drastically change the likely outcome of the game. Instead of the outcome in which no one contributes, the only Nash stable outcome is outcome 16 in which all littoral states contribute but participants from the public or private user sector do not contribute. The outcome in which all contribute is not Nash stable, but it is nonmyopically stable which requires that the user sector buy into some strategic rationale to contribute.

Table 5.6 highlights qualitatively the findings of the case study. For three different risk perceptions which were translated into participants' ordinal preferences over risk management outcomes, the likely risk management outcomes and challenges to achieve the desired resolution are listed. Insights from these findings are discussed further below.

Table 5.6: Summary of case study findings and insights.

Risk Perception	**Risk Management Outcomes (based on GMCR results)**	**Challenge**
If participants recognize that more contributions decrease risk, but none have individual incentive to contribute…	…then zero contribution is very likely. Participants, who are already contributing, however, may continue if they have strategic foresight.	Need to increase contributions.
If no one would contribute and some participants recognize an individual interest to manage risk but others do not…	…then some contributions are very likely. Contributing participants may unfairly shoulder the burden, however, while others benefit.	Need to establish fair policies or mechanisms to allocate costs and benefits.
If some would contribute and others recognize that it is in their interest to contribute as well…	… then cooperative contributions are very likely. Agreements however must be linked to risk perceptions.	Need to maintain interest and adapt to emerging conditions.

Insights from connecting GMCR models with risk perception models

These results are instructive because they provide participants in the Cooperative Mechanism with insights on the conditions required to secure contributions. The conditions based on the Tragedy of the Commons model are that more than one DM must decide to contribute and that they must have forethought. However, since any outcome in which more than one player contributes is stable, these conditions are not enough to increase the number of contributors. Rather, as shown for the littoral states, if all participants in the user sector perceived that more contributions would reduce their own risks, then their preferences would be to strategically contribute on their part rather than not. As a result, the most likely risk management outcome would be for all to contribute. Developing the system models for user sector participants' further to communicate risks according to their objectives may be done to influence a change in their risk perception. Indeed, this is the challenge that Singapore, Malaysia, Indonesia and Japan are trying to overcome through the Cooperative Mechanism which tries to involve more user states and the shipping community. The challenge may be surmounted, as shown here by connecting the understanding of risk perception to preferences in deciding one's risk management strategy. System models communicate participants' risk perceptions. The likely risk management outcome predicted by a GMCR model feeds back into participants' risk perception models to ascertain whether preferences were correctly specified according to the resulting consequences. These results may show that participants' preferences are different. By presenting the risk situation and likely risk management outcome in an explicit model, participants' perceptions and preferences may also be changed in effect. As shown here, by understanding risks in relation to one's own and others' preferences, the outcome of the so-called Tragedy of the Commons game can be significantly changed.

This involves connecting the model template in Figure 5.5 with the GMCR model of strategic interactions described above. The augmented model is illustrated in Figure 5.9. In considering the likely risk management outcome of all participants, foreseeable negative consequences based on a risk perception model could change participants' preferences. The process uses system models to navigate through the complexity of multiple perspectives in a SoS. Participants cope with uncertainty by assuming that anything is possible as a threat or

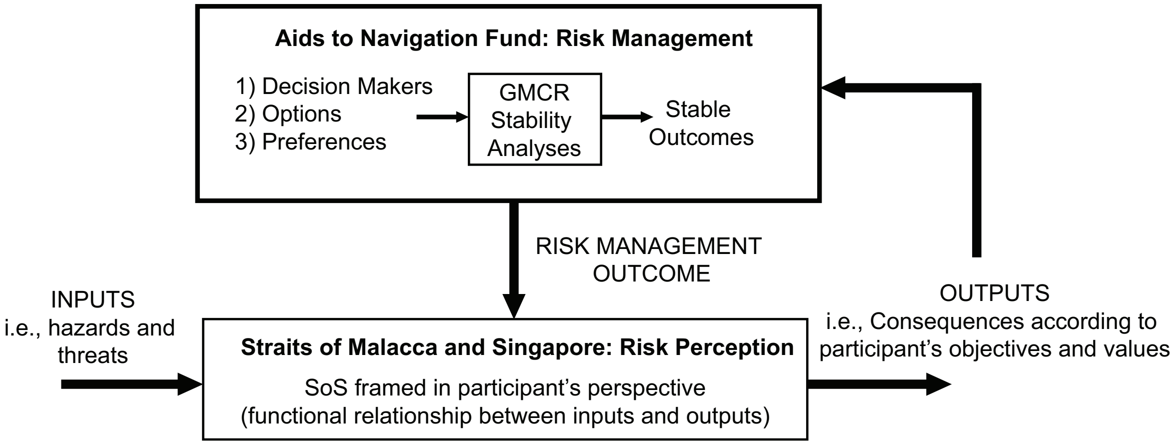


Figure 5.9: Conceptual feedback model of strategic interactions among participants in the management of risks in the Straits of Malacca and Singapore.

hazard and focus on the effectiveness of collective risk management actions. Participants deal with ambiguity by negotiating risk management outcomes in relation to the frames of their system models. The process integrates a GMCR model to show participants the likely outcome of their strategic interactions, which when placed back into a meaningful frame (their own risk perception model) can help to direct participants towards the desired risk management solution. In fact, this is exemplified in considering Japan's strategic interactions with the littoral states. Japan has historically supported the littoral states since the 1960s in maintaining navigational aids. This is likely for strategic rather than altruistic reasons because much of Japan's energy supply traverses the Straits of Malacca and Singapore. Japan's preferences would be different from the ones specified for a Tragedy of the Commons game, in that it would prefer to contribute than not, just like the littoral states. If the littoral states and Japan could find similar strategic reasons for the user sector, then it would follow that the only stable outcome (outcome 32) would be for everyone to contribute. The GMCR platform can thus be used to test the effectiveness of proposed solutions at bringing about the desired risk management outcome.

The model of strategic interactions among DMs was presented at the November 2010 workshop on risk governance of maritime global critical infrastructure focused on the Straits of Malacca and Singapore. The goals of the workshop itself were to identify risk governance deficits and recommendations using the framework developed by the International Risk Governance Council (IRGC, 2010). The SoS engineering methodology was introduced to get workshop participants thinking about the development of solutions that would be candidate recommendations for addressing the free-rider problem in the Straits. Not much time was available to actually explore potential solutions, but the response from participants affirmed the need to better integrate risk assessment with decision making and to consider the broader strategic interactions among key players in order to assess risks with relation to their preferences.

As policy plays an important role for coordinating participants, it would be interesting to compare the effectiveness of different policies on the risk governance process. For example, which policies help participants to reach the desired risk management outcome in which everyone contributes? Since this has not yet been formally done, one could take the policy solution that has been suggested by the Nippon Foundation, which is a formula of one cent per deadweight tonne for calculating voluntary contributions from the shipping industry to the Aids to Navigation Fund of the Cooperative Mechanism (Ho, 2009), and determine conditions on risk perceptions that would make it strategically rational to contribute rather than not. The results would serve as a benchmark to compare other alternatives. Another policy solution might be a formula for specifying the portion of port dues that could be contributed by port authorities to the fund based on the connectedness of the port to the Straits. The solutions would have to be linked to the risk perceptions and in turn to the preferences of the participants. The proposed model and methodology provides a framework on which to make this connection and to encourage key players to interactively engage in the process of developing more detailed solutions for the management of the risks in the Straits of Malacca and Singapore, which constitutes a critical interface in the maritime global transportation SoS.

5.5 Summary of Contributions

In the probability-consequence plane of risk, extreme events are usually plotted in the corner where extremely low probabilities and extremely high consequences intersect. However, multiple participants are likely to have disagreements over extreme risks because of underlying knowledge gaps in understanding affected systems, in identifying and precisely quantifying consequences and assessing probabilities. Disagreements are to be expected, but rather than wasting time and resources arguing over the risk estimation, stakeholders should focus on system identification and in communicating their different perspectives of the system. Also, given that incommensurable perspectives may be persistent, rather than being gridlocked in inaction, a normative stance to seek out strategically stable risk management outcomes was adopted in this work.

A SoS engineering methodology was proposed to integratively develop an augmented model of the problem that considers both risk to the system through different frames and the strategic interactions among participants in risk management. The methodology requires the participation of experts, managers, policy makers, and modelers to adaptively refine pluralistic system models and to search interactively for solutions that lead to desired risk management outcomes that are strategically stable. The case study on maritime global critical infrastructure focusing on the Straits of Malacca and Singapore affirms the need to integrate preferences and risk perceptions so that potential solutions can be tested adaptively and brought to bear on the risk management of global maritime critical infrastructure.

Altogether, the SoS engineering methodology encompasses a philosophy to address risk in all of its dimensions of ambiguity, complexity and uncertainty. As a result, risk management is interlaced with value-focused and strategic thinking. The work presented in this chapter provides a foundation to extend the preferences construction methodology in Chapter 3 to consider risk perception and to extend the ABMS framework for modeling competitive and cooperative behaviour under conflict to probabilistic assessment of policies. In the next chapter, the main contributions of this thesis are summarized and ideas for future research endeavours are brainstormed. ■

Chapter 6

Conclusions and Future Research

As outlined in Figure 1.2, this thesis presented a policy development framework based on SoS thinking, as well as operational SoS methodologies to model value systems, harness complexity of conflict, and finally, confront risk assessment and management. A summary of the main contributions of each chapter is provided in Section 6.1. Finally, directions for future research are suggested in Section 6.2.

6.1 Main contributions of this thesis

Overall, this body of work advances the understanding of SoS engineering concepts and modeling of values, complexity, and risk in a SoS. Moreover, the proposed SoS engineering methodologies constitute a toolbox for practically addressing SoS challenges through the design of integrative, adaptive and ethical policies. The main contributions of this thesis include a formal policy development framework based on SoS thinking, a dynamic and contextual preferences construction methodology, an agent-based framework for modeling competitive and cooperative behaviour under conflict, and a SoS engineering methodology for risk management.

In Chapter 2, a formal policy development framework was developed based on a review of SoS thinking to systematically address, in an integrative and adaptive fashion, major 21st century challenges, such as the global food crisis, and their interactions with other key natural, societal, and technological systems. A SoS approach was defined to respect the different value systems of multiple participants, to harness complexity through effective integration, and to engage the world of uncertainty and unpredictability with an adaptive response. Faced with the present global challenges, it was identified that strategic and operational methods are needed to develop ethical policies, enhance integrative and adaptive management practices, and direct conflict resolution in a positive direction. Participants in a SoS need tools to model and analyze complex systems which they are trying to responsibly govern, taking into account values and risks to design and evaluate different policies. A preliminary investigation into the global food system was undertaken to understand the SoS and to provide insights on how to carry out policy development using the proposed framework.

In Chapter 3, a systems methodology was proposed for constructing ordinal preferences from a value system. The methodology employs value-focused thinking, the analytic hierarchy process, and a variety of methods to capture different value judgments. The methodology is operationalized for integration with GMCR, which facilitates modeling and analysis of strategic conflicts. In applying the proposed methodology, preferences can take into account evolving contextual variables in order to simulate participants' responses in a dynamic environment. The effects of different value systems on preferences and resulting conflict dynamics were demonstrated for a generic CPR dilemma.

In Chapter 4, a novel agent-based framework was presented for modeling and simulating competitive and cooperative behaviour under conflict. Formal definitions were introduced for Nash, general metarational, symmetric metarational and sequential stability decision rules, which reflect human behaviour under conflict. The definitions were inspired by the solution concepts of GMCR and conceived for implantation in the proposed ABMS framework. Using these decision rules, competitive and cooperative conflict dynamics were simulated for the theoretical CPR dilemma introduced in Chapter 3. With preferences and options of DMs as input, strategic interactions under different decision rules can be investigated to determine possible conflict evolutions. Moreover, policies can be tested for their effectiveness in avoiding or recovering from a Tragedy of the Commons.

In Chapter 5, a SoS engineering methodology was synthesized for risk management of extreme risk in a SoS. Such risks are fraught with complexity, ambiguity, and uncertainty, which pose challenges in how participants perceive, understand, and manage risk of extreme events. The domain of risk analysis was expanded to consider strategic interactions among multiple participants. System models are utilized to model risk perception. Consequences, hazards, threats, and risk management strategies are connected to the state of the SoS. Moreover, GMCR models are used to determine likely risk management outcomes as a result of participants' preferences which are affected by their risk perceptions. A practical application of the SoS engineering methodology was demonstrated in part by a case study of a maritime infrastructure SoS, namely, the Straits of Malacca and Singapore.

Altogether, the SoS engineering framework and suite of methodologies to operationalize SoS thinking make significant contributions to the knowledge base of systematic policy design and state-of-the-art in modeling strategic behaviour and simulating conflict dynamics.

6.2 Future research

The developments of this thesis unlock new opportunities to further the state of knowledge in decision analysis, complex systems, SoS engineering, conflict resolution and risk management and to improve standard practices in policy development. Below are some possible directions for future research.

1) A retrospective study of the global food crises of 2008 and 2011 could be undertaken to model the value systems and complex interactions which played a crucial role in creating vulnerabilities and decreasing resilience in the global food system. Furthermore, a prospective study of global food security using the SoS engineering methodology for risk analysis could be demonstrated as an aid for negotiations on reforming international trade rules and national agricultural policies.
2) Numerous important, but not global, problems could also be analyzed with SoS thinking and solutions may be synthesized from insights obtained from operational models. Important problems or issues to address may be identified for the City of Waterloo, the University of Waterloo, or a private enterprise.
3) The preferences construction methodology for ordinal preferences can be modified to produce cardinal preferences. Strength of preference and uncertainty of consequences may be factored into decision making by employing utilities and expected utilities, or by other preference structures such as the one formulated by Xu et al. (2007, 2009a, 2010a, 2010b). This research direction may lead to complementary techniques of probabilistic assessments in agent-based modeling and simulation.
4) Alternatively, the preferences construction methodology for ordinal preferences can be extended to consider risk perception to incorporate uncertainty of consequences

into decision rules. Some techniques to investigate include influence diagrams, Bayesian networks, value of information, fuzzy methods and neural networks. Similarly, this research direction would be complemented by parallel developments in ABMS.

5) Computational complexity of strategic decision rules increases exponentially as more participants and more options are added to agents' GMCR models. New computational methods such as the matrix representation of GMCR (Xu et al., 2007, 2009b, 2009c, 2010c) can significantly decrease calculation times. Hence, efficiency of the implementation of the ABMS framework may be improved by incorporating matrix representation of GMCR, which would require corresponding derivations of the decision rules formulated in Chapter 4.
6) Using the ABMS framework, situations in which there is heterogeneity of value systems, decision making behaviour, and risk perceptions can be modeled and simulated. It would also be interesting to investigate situations in which there are misperceptions or misinformation.
7) There exists a rich literature of concepts developed for conflict resolution which can be incorporated into the ABMS framework. Some areas for further ABMS development include the effect on outcomes of power relationships among participants such as hierarchical power (De et al., 1990, 1994); the perception of different forms of justice (distributive, procedural, transitional) on the durability of outcomes (Druckman and Albin, 2011; Albin and Druckman, 2012); and the role of "third-parties" with respect to their options such as creating forums for dialogue, sanctioning direct opponents in a conflict, and proposing agreements, as well as their preferences in mediating conflicts (Bercovitch, 2009; Peck, 2009; Crocker et al., 2009).
8) Using the rich and extensive literature of empirical/experimental research and field studies on CPR, the ABMS framework presented in this thesis can be utilized to model and simulate real-world CPR dilemmas. New models can be calibrated with and validated against empirical data. Moreover, the ABMS framework can be extended and further developed to capture important details that are specific to particular CPR situations. Furthermore, new hypotheses can be tested and results may

potentially be generalizable to advance the theory of institutions and collective actions.

9) It would be desirable to run full-scale sensitivity tests and exploratory simulation experiments that are designed according to the goals of a specific real-world case study. Heuristics may need to be developed in order to constrain the solution space so that models are meaningful and practical.
10) Data visualization techniques need to be developed in order to display results from the agent-based conflict models and simulations in a manner that is meaningful to participants in a conflict. Moreover, the readability of results would be greatly enhanced if the encoding of a single conflict state was a symbol rather than a decimal number.
11) More case studies, such as negotiations on addressing changes in climate and handling chemicals of emerging concern, could be investigated with the SoS engineering methodology for risk management. It would be desired to further demonstrate the iterative approach of the SoS engineering design process in which participants progress from an undefined, conflict-ridden and highly uncertain problem towards a culture of understanding different value systems, harnessing complexity, and developing the knowledge needed to effectively deal with challenges of ambiguity, complexity and uncertainty.

The human capacity for working together to achieve mutually beneficial gains remains as one of the most important facets of humanity’s ability to make progress. Moving forward, the capacity for harnessing complexity through conflict resolution and managing risks integratively and adaptively within an ethical framework will continue to increase in importance. Such progress is crucial for solving our increasingly complex and dynamic problems. ■

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Appendix

Appendix A

Export prices of rice, wheat, and maize, 1961-2008

YEAR	Rice[b]	Wheat[c]	Maize[d]
1961	137	60	46
1962	153	60	51
1963	143	59	55
1964	138	64	56
1965	136	58	55
1966	163	62	59
1967	206	62	50
1968	202	58	49
1969	187	56	54
1970	144	63	58
1971	129	62	58
1972	147	69	56
1973	350	137	98
1974	542	178	132
1975	363	138	120
1976	254	123	112
1977	272	96	95
1978	368	125	101
1979	334	156	116
1980	434	191	125
1981	483	196	131
1982	293	167	109
1983	277	170	136
1984	252	165	136
1985	216	173	112
1986	211	161	88
1987	230	134	76
1988	301	180	107
1989	320	201	112
1990	287	156	109
1991	313	143	107
1992	287	177	104
1993	270	193	102
1994	268	199	108
1995	321	207	124
1996	339	231	166
1997	303	181	117
1998	304	163	102
1999	248	151	90
2000	202	147	89
2001	173	152	90
2002	192	176	99

YEAR	Rice[b]	Wheat[c]	Maize[d]
2003	198	177	105
2004	238	187	112
2005	286	198	99
2006	305	217	122
2007	326	300	164
2008	650	455	223

a fob = free on board. b 5% brokens, milled, fob Bangkok. c Canadian No.1 Western Red Spring 13.5%, in store Thunder Bay, domestic, from 1985 St. Lawrence export. d US No.2 yellow, fob Gulf ports.

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