SEEING THE REST OF THE COMMUNITY: USING COMPLEX SYSTEMS TO REVEAL THE STRUCTURE AND FUNCTION OF INTERDEPENDENCE

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ABSTRACT

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Interdependence occurs when autonomous elements of a system interact, enabling the emergence of an overall system and its behavior. The humbling act of studying interdependence requires a shift from a reductionist world view that understands reality through its components. Instead, it holds that we can only understand reality by accounting for the whole and appreciating its components' mutual interaction. Studying the patterns that underlie interdependence can yield insights into causal dynamics revealing how structure can lead to innovation, novel system states, and problems resistant to intervention.

......In this dissertation, I present three studies to broaden the literature on how complex systems and systems thinking can unmask the structure and function of interdependence in place-based sustainability problems. In my first study, I examine the field of participatory modeling and use document citation and network analysis to reveal communities of practice in this field. By understanding the connections and communities of scholars in this work, I show the emergence of separate but related research fronts and how they diverge in their approach to participation and modeling. My next two studies are situated in Flint, MI, a community still responding to the water crisis's social-ecological disaster. These studies examine how a community can use systems thinking to elevate and target their positive change efforts. The second study explores how interdependent connections in the network governing the food system can explain the community's capacity to foster social learning, innovation, and

adaptation. It uses the small-world network model to assess social-ecological resilience as a function of a network's clustering and density. My third study deals with system archetypes or system structures that produce characteristic patterns of problematic behavior due to the interdependence of components. Though system archetypes are a well-documented tool for communicating the structure and behavior of systems and have been applied across various contexts, their identification is often difficult. This study demonstrates an explicit process for identifying system archetypes. It uses a qualitative coding scheme adapted from Wolstenholme's (2003) definition of isometric archetypes to elicit structure and behavior from purposive text data generated from a community visioning process. This process increases the narrative's connectedness to the model, which can enhance the modeling process and give specific insights into systems thinking pedagogy and practice.

For C.M.D. and M.E.M. Thank you for being both my compass and guides.

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TABLE OF CONTENTS

LIST OF TABLES ix

LIST OF FIGURES x

Chapter 1 Introduction 1
Introduction 1

Chapter 2 Participatory Modeling Network 4
Introduction 4
Bibliometrics 8
Dataset 11
Results 12
Discussion 16
Conclusion 20

Chapter 3 Connectivity and Social-Ecological Resilience 22
Introduction 22
Small Worlds 24
Stakeholder Mapping 26
Translating Stakeholder Maps to Networks 28
Analytical Methods 31
Results 32
Discussion 34
Conclusion 36

Chapter 4 Translating Narratives into Archetypes 38
Introduction 38
Archetypes 38
Qualitative Research and SD 41
Data Collection 43
Data Extraction 44
Major Stocks 45
Central Actors 45
Behavior 45
Sectors and System Boundaries 45
Structure 45
Problem 45
Action 46
Intended Consequences 46
Unintended Consequences 46
Delays 46
Feedback loops 46
Descriptive Results 48
Examples 49
Underachievement 50
Out-of-control 52

Relative Control ... 54
Relative Achievement ... 56
Discussion ... 58
Conclusion ... 61

Chapter 5 Conclusions ... 62
Introduction ... 62

APPENDICES ... 66
APPENDIX A Stakeholder Mapping Protocol ... 67
APPENDIX B Archetype Codebook ... 68

REFERENCES ... 69

LIST OF TABLES

Table 2-1 Detected Communities in Participatory Modeling.. 15

Table 2-2 Participatory Modeling Compared.. 16

Table 3-1 Descriptive Statistics & Small-World Quotient 33

Table 4-1 Archetypes Descriptive Table.. 48

Table 4-2 Actors and Stocks by Frequency.. 49

LIST OF FIGURES

Figure 2-1 Web of Science Search Terms 11

Figure 2-2 Tree Map of Participatory Modeling 12

Figure 2-3 Participatory Modeling Publications Overtime 13

Figure 2-4 Co-citation Network 14

Figure 3-1 Comparing Degree Distributions Across Networks 29

Figure 3-2 Social Ecological Governance Network 34

Figure 4-1 Comparing Generic and Semi-generic Archetypes 47

Figure 4-2 Generic Archetypes Underachievement 51

Figure 4-3 Generic Archetype: Out of Control 53

Figure 4-4 Generic Archetype: Relative Control 55

Figure 4-5 Generic Archetype: Relative Achievement 57

Chapter 1 Introduction

Introduction

The economist Thorstein Veblen once wrote, "It is always sound business to take any obtainable net gain, at any cost and at any risk to the rest of the community." Though his intention is satirical, the 'rest of the community' is often invisible and difficult to consider. They are invisible not only to business leaders and decision-makers but also to other community actors. Even if we put selfish intent aside, the *rest of the community* goes unseen and unheard. Whether the *rest of the community* is downriver from an operation or scholars circling similar ideas or a generation yet to be born, it can feel impossible to calculate how actions today and here may impact them and there. By taking the study of interdependence seriously, as this dissertation attempts, we can reveal the structure, or the links and connections, to the *rest of the community* and potentially learn to act with them in mind.

A complex systems approach allows researchers to engage with the concept of interdependence. Interdependence occurs when autonomous elements of a system interact, enabling the emergence of an overall system and its behavior. Studying interdependence requires that we account for the whole and appreciate mutual interactions. Studying the patterns that underlie independence can yield insights into causal dynamics revealing how structure can lead to innovation, novel system states, and problems resistant to intervention.

In the social sciences, the concept of "community" can be used to describe geography, affiliation, family structures, and identities of faith, circumstance, or interest (Doberneck, Glass, and Schweitzer, 2010). Often, "community" is used to describe physical locations or as a categorical indicator used to explain variance in opinions or outcomes (Maqueen, et al 2011). Unlike traditional social sciences, complex systems and network science view community as more than an explanatory variable or even the context in which research happens. In this approach community is defined as the structural relational ties that exist in-between individuals. When represented as graphs, communities are present when there is high transitive closure, or when relations between three entities X, Y, Z show closure in that X is connected to Y and X is connected to Z, closure would be when Z and Y are also connected. This approach to community considers the interdependent relationships of individuals, their environments and the social learning that transmits across cultures and spaces.

In this dissertation, I present three studies to broaden the literature on how complex systems and systems thinking can unmask the structure and function of interdependence in place-based sustainability problems. This unifying theme of interdependence creates a space to think critically about the community structures that drive systems.

The first study, Chapter 2, examines participatory modeling and uses document citation and network analysis to reveal communities of practice in this field. Participatory modeling (PM) provides various tools and techniques to represent empirical, theoretical, and experiential understanding using a semi-standardized language. There are many strands of PM literature, here defined as different approaches and methodologies for considering models, modelers, stakeholders, and issues, that span the environmental management, planning, and action research spectrum. Though recent contributions to the PM literature have been able to synthesize trends, there hasn't been a complete systematic review of this literature, and many open questions remain.

Chapter 3 and 4 are scientific contributions that look closely at Flint, MI, a community still responding to the water crisis's social-ecological disaster. These studies examine how a community can use systems thinking to elevate and target their positive change efforts.

Chapter 3 explores how interdependent connections in the network governing the food system in Flint, MI, can explain the community's capacity to foster social learning, innovation, and adaptation. It uses the small-world network model to assess social-ecological resilience as a function of a network's clustering and density. Using descriptive network measures examines how the Flint food system responds to crisis, how it can improve and harness the power of the community's collective assets. Chapter 4 looks closely at the concept of system archetypes or system structures that produce characteristic patterns of problematic behavior due to the interdependence of components. Though system archetypes are a well-documented tool for communicating the structure and behavior of systems and have been applied across various contexts, their identification is often difficult. This Chapter is motivated by a desire to create accessible systems science employed in community contexts. This study demonstrates an explicit process for identifying system archetypes. It uses a qualitative coding scheme adapted from Wolstenholme's (2003) definition of isometric archetypes to elicit structure and behavior from purposive text data generated from a community visioning process. This process increases the narrative's connectedness to the model, enhancing the modeling process and giving specific insights into systems thinking pedagogy and practice

By studying community as the result of interdependent relationships, we can begin to understand the intersecting environments and conditions that either promote or hinder health, environmental conditions, and general well-being.

Chapter 2 Participatory Modeling Network

Introduction

Participatory modeling (PM) is an increasingly popular approach to including stakeholders in defining, analyzing, and managing socio-environmental issues. Modeling provides a variety of tools and techniques to represent empirical, theoretical, and experiential understanding using a semi-standardized language. Scholars have acknowledged that there are many strands of PM literature, here defined as different approaches and methodologies for considering the role of models, modelers, stakeholders, and issues that span the environmental management, planning, and action research spectrum(Gray et al., 2018; Lynam, Jong, Sheil, Kusumanto, & Evans, 2007; Voinov et al., 2016). The approaches may also differ in how structured or prescribed the participatory process tends to be. They pull from different lines of participatory literature and have lineages in different types of modeling. However, there is no broad level systematic synthesis that examines these different strands analytically.

PM is unified across broad approaches in its epistemological orientation and appreciation of knowledge integration across conceptual, expert, and experiential dimensions. This orientation provides a framing in that explicit representation of knowledge (or models) is an important way to learn about knowledge and to create objects that facilitate dialog and further insights (Boundary Objects). PM approaches hold that knowledge can be attained and understood by exploring diversity and convergence of thought related to complex issues. The practices are also united in their problem orientation and in their application to complex or wicked problems, which are dependent on context-specific circumstances with interacting forces, and are resistant to singular solutions (Rittel & Webber, 1973).

Participatory modeling approaches are also aligned in their orientation and application of systems thinking. Systems thinking is a way to view a problem and its causes as a whole system, recognizing that the patterns and cycles of behavior are a result of interrelated components and how they change over time (Meadows, 2008). Using systems thinking skills can add perspective to wicked problems and address the helplessness often associated with them. It can take abstraction and provide an understanding and ability to find solutions to the root causes of problems (D. H. Meadows, 2008; Stave, 2003). Because of these features, all strands of participatory modeling are appropriate and well suited for conducting sustainability science research--or place-based, problem-oriented form of inquiry with the goal of linking knowledge creation to actions that advance ecological and social wellbeing (Miller, 2013). Scholars in sustainability science and ecological modeling have attempted to synthesize some of the PM literature, though not in a systematic way (Gray et al., 2018; Naivina, W., Le Page, M., Thongoi, M., Trebuil, n.d.). In a review by Gray et al. (2018) they show that PM does not share a consensus on how participation is framed, though they reference how authors who have attempted to clarify how processes work while maintaining the flexibility to adapt to constraints of problem, sector, and modeling tool kits. Voinov & Bousquet (Voinov & Bousquet, 2010) describe PM as the use of an assortment of tools to have participants create formalizations of knowledge. These formalizations (or models) can take the form of collective diagrams, rich-pictures, or individual representations of mental models.

Beyond representation, PM may use participation to inform or interact with simulation models, and graphically represent a distributional understanding of populations under high uncertainty using local or indigenous knowledge. Voinov & Bousquet (2010) contend that because of the human dimensions of PM, there can be no unique guidance or methodology to inform PM on how to create meaningful engagement of all participants. Though they briefly give an overview of participatory action research and other methodologies for engaging with stakeholders, they contend that the human dimensions require more flexibility for modelers. They do, however, provide an adaptable and detailed analysis of the necessary components and principles for a participatory modeling process. Voinov et al. (Voinov et al., 2016) argue that there remains a gap in guidance articles for practitioners regarding the tools, methods, and processes used in PM. They write that the "current lack of guidance is, in part, the result of our highly diverse human society that retains a heterogeneous distribution of knowledge and highly localized believe systems."

Voinov & Bousquet (2010) offer two summary objectives that often motivate PM. The first being to increase and share knowledge of a system, and secondly, to identify and clarify the impacts of a solution to a given problem to support decision making, policy, or management. Voinnov et al. (2016) expand on the ambiguity of the participatory process and motivations in PM by noting, "… articles document the development of new tools and methods in a particular case study rather than critically assessing the stakeholder engagement process per se. This is not a trivial issue..."

Answering some of these issues of guidance, Voinov et al. (2018) outline the methods and tools used in PM and Gray et al. (2018) provide the 4P framework to "…help design and assess all cases of PM…." The 4P framework includes the Purpose (1) for selecting PM, the Process (2) by which the public was involved, the Partnerships (3) formed, and the Products (4) from the efforts. The 4- frameworks intended purpose is to assist in the Synthesis and reporting of PM projects across tool-based paradigms, subfields, or publishing outlets. The 4p framework can be helpful in understanding what is similar in these practices, what is different, and what can be learned across the emerging field of practice.

In the 4P Framework, purpose is specifically related to two dimensions of why a PM process was chosen, it includes the justification for why PM is used and the defining issue that the model hopes to elucidate. Clarity is needed in these separate respects to understand when *participation* is necessary and when *modeling* is necessary. As with many aspects of applied social-ecological research, beginning with a rich description of the problem statement directs and informs the research direction, methods, and theories employed in the work. Beyond the 4P Framework, other authors in the PM literature have put emphasis on clarifying the purpose of PM. Voinov and Bousquet (2010) contend that "Stakeholder engagement, collaboration, or participation, shared learning or fact-finding, have become buzzwords and hardly any environmental assessment or modeling effort today can be presented without some kind of reference to stakeholders and their involvement in the process" (p. 1268). They refer to two major objectives specific to environmental modeling with stakeholders, one being to increase and share knowledge of a system under a variety of conditions, and the other to increase stakeholder buy-in of potential solutions. However, the range of goals of a PM process can vary and may explain differences in practice and orientation.

Though recent contributions to the PM literature have been able to synthesize some of these trends, there isn't a complete review of this literature, and many open questions remain including what literature informs the practice, what types of problem spaces is PM helpful, and what practices guide the participatory processes. This emerging interdisciplinary field could benefit from a clear examining of the PM literature through the lens of the 4 P's framework in a systematized process. A synthesis can help explain how these divergences in practice manifest in conceptualized and actualized purposes employed.

Bibliometrics

Bibliometrics is the quantitative analysis of the nature and course of scientific discovery and disciplines. It uses the documents of science and inquiry (books and research articles, etc.) to understand their bibliographic content. Pritchard (1969) first introduced the idea of bibliometric analysis as "the application of mathematics and statistical methods to books and other media of community" (Pritchard, 1969 p 348-349). Bibliometric methods include areas of citation analysis, content analysis, and network science. While these tools are often used in the field of information and library science there has been an expanded use in applying it to other areas. Emerging fields have used bibliometrics to explore and explain the prominence of certain works, scholars, and ideas. These techniques are increasingly used to map science as a structure of knowledge and view discovery of knowledge as multifaceted communication(Pritchard, 1969).

De Solla Price (1985) coined the concept of the research front in his seminal paper on the topic. In Price's conceptualization, the tendency for scientists to cite the most recently published articles on a topic creates citation networks that are very dense and relevant to specific aspects and contributions of research. Research fronts can be seen as the pockets of science in a given domain that describe specific knowledge creation that is being communicated through scholarly products.

Citation Analysis (CA) is a method developed by bibliometric scholars to identify areas of scholarship and has been used in areas of interdisciplinary research to understand relationships and trends in the literature (Leydesdorff, 1998; Trujillo & Long, 2018; Yan, 2012). It allows the researcher to construct a network based on features of the citing and cited literature of each document. This process reveals patterns in the document dataset and has been used to identify research fronts and emerging communities of practice. Citation analysis uses citations as a way to understand the evolutionary, versus historical context of knowledge development. It views science as a knowledge object being continuously reconstructed through the reflexive rewriting of histories in the light of new empirical findings (Leydesdorff, 1998).

Co-citation analysis, a form of citation analysis, constructs networks of documents where edges are based on shared citing literature. The associations here are inferred based on the level at which other documents cite a set of works (Yan, 2012). Bibliographic Coupling (BC), like co-citation analysis, is a method for understanding fields of research that specifically looks at the development of a field or research front (Kessler, 1963). It looks to the past and constructs relationships based on documents co-citing work. This allows us to consider what literature is central to the framing of the scholarship, what methods are being used, and what topic areas are relevant to a particular group.

Though similar, BC and CCA construct networks with different structures and have different purposes. BC can tell us more about the development of the research front by explaining what literature informs scholarship. CCA is more forward looking, and captures the relationships based on how documents are being co-cited. Boyack (2010) empirically tested CCA and BC to determine which network allows for the most accurate detection of front of fields. They find that though BC most accurately finds research fronts in fields with a long history, and that CCA can be helpful when identifying new or emerging fields (Boyack, 2010). For the purposes of PM it is necessary to understand where the strands of practice come from and if new fields of practice are emerging.

In network science, Community Detection Algorithms (CDA) or modularity assessments, are a set of algorithms that consider connections and the presence of transitive relationships to identify sub-groups (clusters) within a larger network (Fortunato, 2010; Girvan & Newman, 2002; Porter, Onnela, & Mucha, 2009). It is a method used to identify modules and hierarchical structures based on the topographic network information. Community structure is key to understanding how networks function and to analyze patterns of connection (Porter et al., 2009). For the purpose of this research, these communities are groups that tend to cite documents in similar patterns. Newman (2004) describes modularity as the fraction of edges (or links) in a network that connect nodes (here documents) controlling for the expected value of the same quantity in a network when random connectivity is assumed between nodes in the same cluster. CDA can be used with networks created with BC and CCA to identify the research fronts in PM and create the context for the cross-comparative analysis. Within bibliometrics research co-citation clusters within a coherent field represent research foci and specializations (McLevey & McIlroy-Young, 2017).

To understand and ascribe meaning to the different groups we found in the networks we followed a similar protocol outlined in Trujillo & Long (2018). Where we identified important works in the detected modularity groups through an analysis of centrality. Here centrality refers to the top frequency of co-cited works by degree. The high centrality score of weighted edges indicates that a document received recognition among scholars in that identified community. The top three works in each modularity group will be evaluated for inclusion in a qualitative analysis. To be included in the final analysis the article needs to (1) be a paper that deals with participatory modeling in a way that deals with stakeholder groups creating formal to semiformal representations of systems and (2) describes in empirical terms the process at which the modeling took place.

Dataset

To create the corpus data-set we included as many documents within the domain of PM as possible. As noted above, PM is an interdisciplinary form of scholarship that includes many disciplinary homes and venues. Web of Science was the search platform used for its wide coverage of scientific fields and capability to provide citation information in meta-data. The proposed dataset was created by Web of Science Core Collection using the "All Fields" search with the following criteria for all languages, though only the English variants of search terms were used. "Modeling" and "modelling" were used in all variants due to regional spelling differences. This search resulted in 1,117 records after filtering to include articles, reviews, books, conference papers, and structured abstracts. The corpus largely consists of articles (813), conference/meeting papers (363) and book chapters (58).

Figure 2-1 Web of Science Search Terms

Web of Science Core Collection for the search terms:

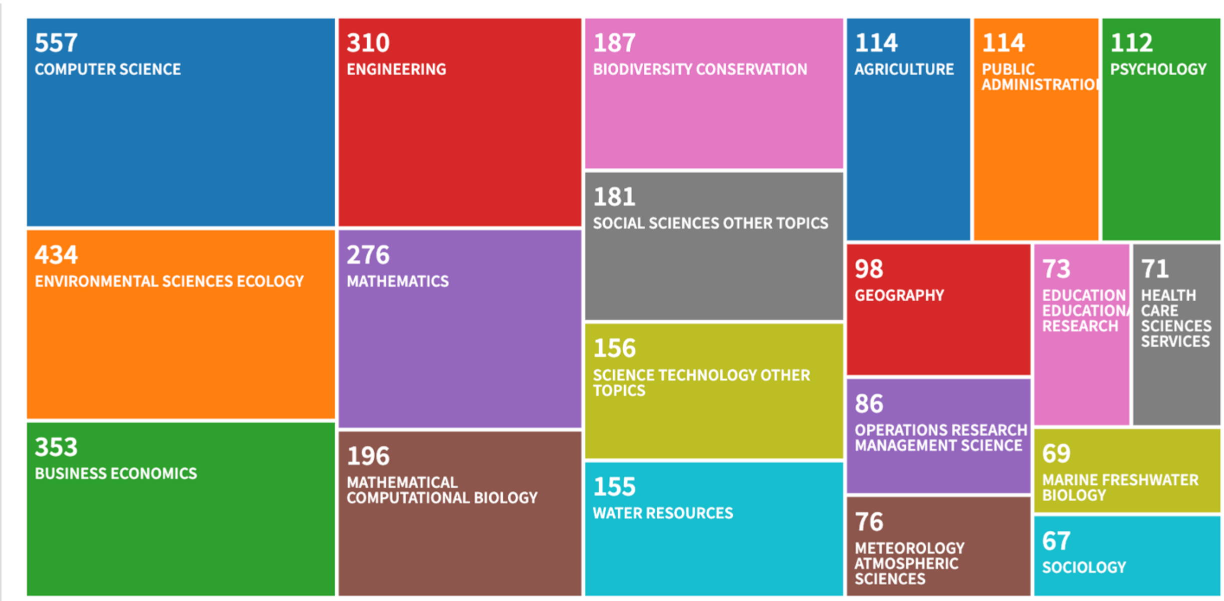
***TITLE:** ("participatory modeling") OR **TITLE:** ("participatory modelling") OR **TOPIC:** ("participatory modeling") OR **TOPIC:** ("participatory modelling") OR **TITLE:** ("Group Model Building") OR **TOPIC:** ("group model building") OR **TITLE:** ("Collaborative Modeling") OR **TOPIC:** ("Collaborative Modeling") OR **TITLE:** ("collaborative modelling") OR **TOPIC:** ("collaborative modelling") OR **TITLE:** ("companion modeling") OR **TITLE:** ("companion modeling") OR **TITLE:** ("companion modelling") OR **TOPIC:** ("companion modelling") OR **TITLE:** ("mediated modeling") OR **TOPIC:** ("mediated modeling") OR **TITLE:** ("mediated modelling") OR **TOPIC:** ("mediated modelling") OR **TOPIC:** ("participatory system dynamics") OR **TITLE:** ("participatory system dynamics") OR **TOPIC:** ("participatory agent-based") OR **TITLE:** ("participatory agent-based")*

***Timespan:** All years. **Databases:** WOS, BIOABS, BCI, CABI, CCC, DRCI, DIIDW, FSTA, KJD, MEDLINE, RSCI, SCIELO, ZOOREC.*

Results

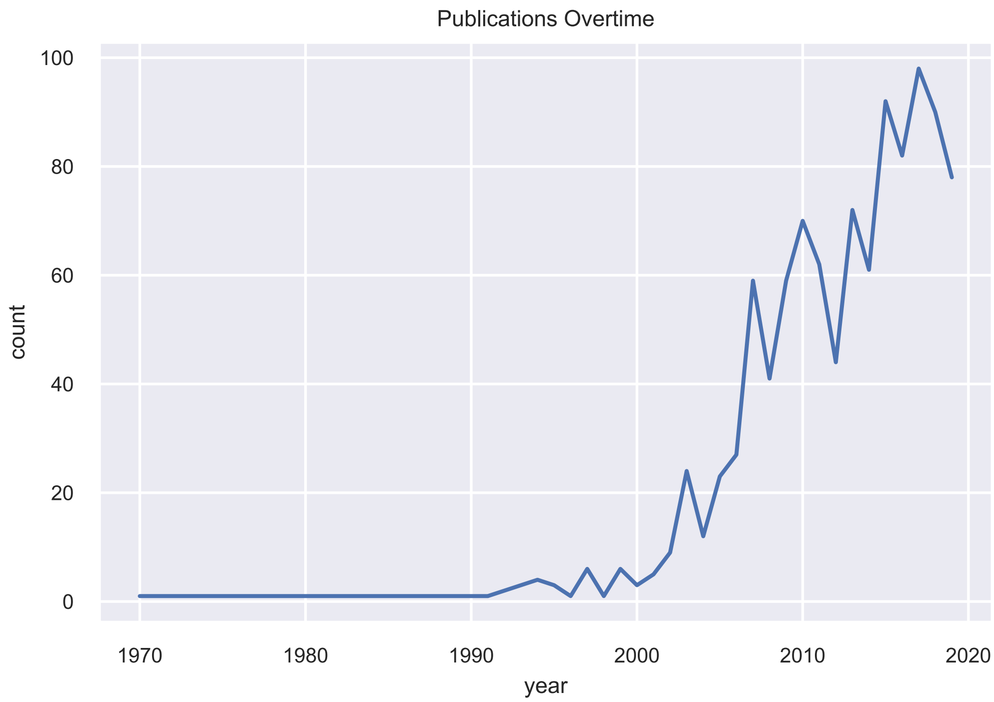
Figure 1 displays a tree map of the field categories classified by Web of Science for the PM corpus. Here we see that the interdisciplinary nature of PM is represented with computer science, environmental sciences, and business representing over a third of the corpus. Integrative social sciences, including sociology, public administration, psychology, make up another third.

Figure 2-2 Tree Map of Participatory Modeling



The corpus contains 1,117 documents representing the range of disciplines in PM. The source documents have a varied distribution of publication dates with a strong trend beginning in the mid 1990s reflecting a the fairly recent growth of this field in recent years. Table 1 shows the top authors, journals, and documents in the corpus based on citations. This description of the corpus serves as a preliminary check that no subfields of PM are being excluded systematically by the query or the indexing of the database.

Figure 2-3 Participatory Modeling Publications Overtime



These core documents cite a total of 28,940 unique documents. However, because we are interested in the subfield of PM and not uncovering the larger mapping of the scientific community, we focus on the connections within the internal core of the corpus. Within the core we have 405 documents co-cited with 587 links. To further refine the data for visualization purposes, we removed weak connections of co-citing >3 times. This leaves 143 uniquely cited documents and 579 links between them. This network is visualized at this trim level in Figure 2. This graph represents the co-cited documents as nodes and the frequency of co-citation as weighted links or edges. Size of the node represents degree and coloring reflects detected communities.

Figure 2-4 Co-citation Network

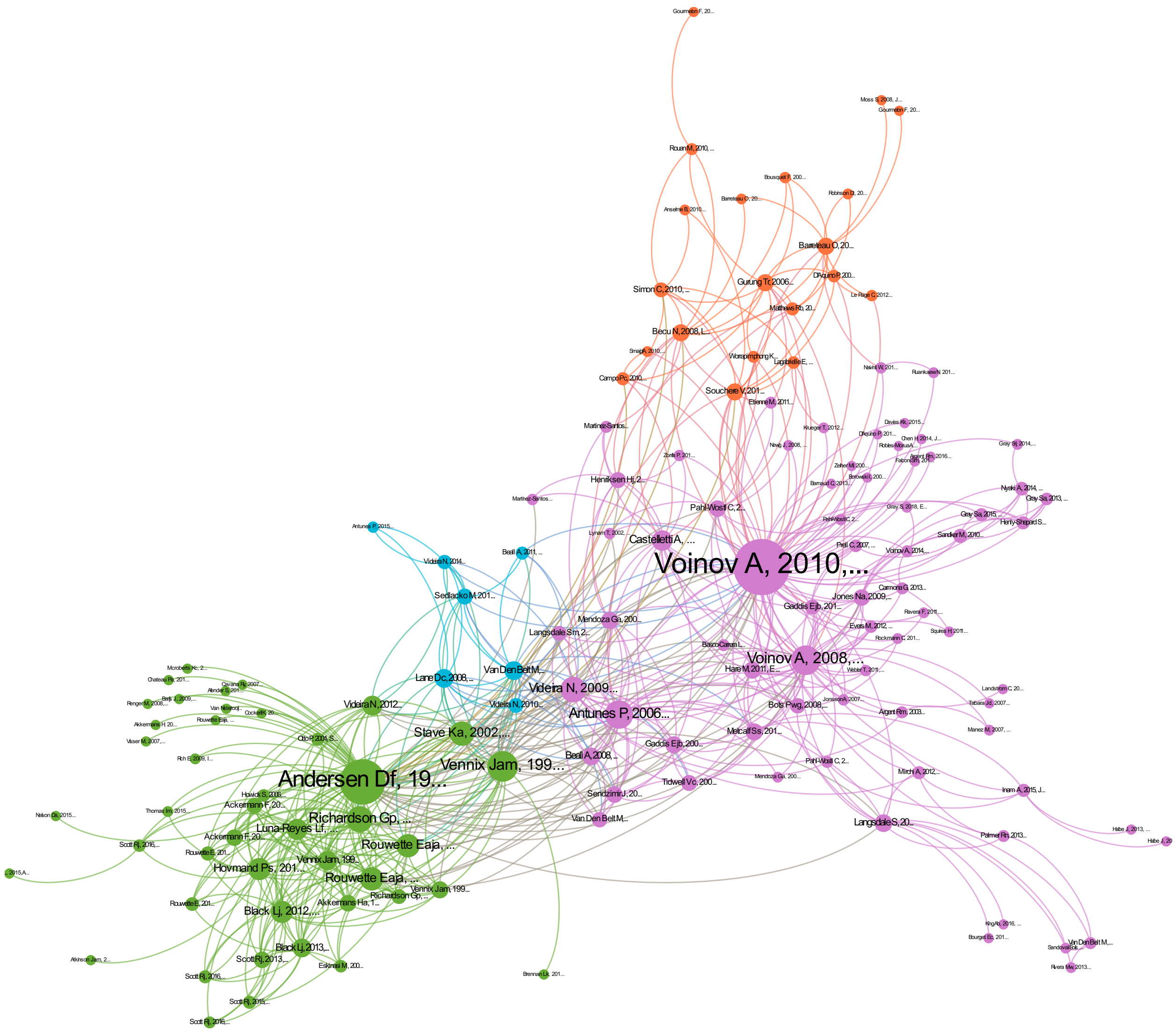


Table 2 reports bibliographic information for the three most frequency co-cited document by degree across each identified community groups. Data is reported as follows: “cited” refers to the number of source documents citing this document, and degree is the number of other documents jointly cited within the core PM documents. For instance, “Voinov A, 2010” represents the largest degree and cited document in community 1, being least three times with 82 other documents in the core.

Table 2-1 Detected Communities in Participatory Modeling

Community Group	Sum of Degree	Count of Id
0	**137**	**6**
Antunes P, 2006, LAND USE POLICY	33	1
Videira N, 2009, ECOL ECON	28	1
Stave Ka, 2002, SYST DYNAM REV	26	1
Videira N, 2012, SYST RES BEHAV SCI	18	1
Van Den Belt M, 2010, ANN NY ACAD SCI	16	1
Lane Dc, 2008, SYST RES BEHAV SCI	16	1
1	**176**	**6**
Voinov A, 2010, ENVIRON MODELL SOFTW	82	1
Voinov A, 2008, ECOL MODEL	35	1
Castelletti A, 2007, ENVIRON MODELL SOFTW	19	1
Langsdale S, 2013, J AM WATER RESOUR AS	14	1
Metcalf Ss, 2010, ENVIRON MODELL SOFTW	13	1
Hare M, 2011, ENVIRON POLICY GOV	13	1
2	**61**	**5**
Souchere V, 2010, ENVIRON MODELL SOFTW	13	1
Barreteau O, 2003, JASSS-J ARTIF SOC S	13	1
Becu N, 2008, LAND USE POLICY	13	1
Gurung Tr, 2006, ECOL SOC	13	1
Simon C, 2010, ENVIRON MODELL SOFTW	9	1
3	**177**	**5**
Andersen Df, 1997, SYST DYNAM REV	63	1
Vennix Jam, 1999, SYST DYNAM REV	37	1
Richardson Gp, 1995, SYST DYNAM REV	29	1
Rouwette Eaja, 2011, SYST DYNAM REV	24	1
Rouwette Eaja, 2006, SYST RES BEHAV SCI	24	1
Grand Total	**551**	**22**

Table 2-2 Participatory Modeling Compared

	Purpose	Process
GMB		
Mediated Modeling	• Building consensus and conflict resolution in social-environmental management issues • Team building and learning, consensus building, communication tool, decision support for policy and management	• lineage in the design-oriented action research field and uses an action-reflection cycle to understand the MM process as it is initiated and proceeds with each group • Knowledge is represented through aggergation and consensus
CBSD	• Create a community of practice around a model, to design innovations that the community will advocate for and implement • Not represent an actual system, but the perceptions of that system; to give voice to those who are disempowered, or to teach self-actualization.	• Places participants in the role of researcher, modeler, and interpreter of modeling results
GMB	• Model quality, stakeholder buy-in, and the likelihood that actions are taken based on modeling insights	• Highly structured processes that involve the use of facilitation scripts to illicit causal system-level understanding from stakeholders (Scriptopedia) • Structured facilitation aimed at codifying the system from scratch.
ComMod	• Cogenerate knowledge about decision processes, common pool resources, and coordination efforts among various agents • Modeling as an intermediary object to facilitate collective and interdisciplinary thought • Support collective decision-making processes • Create a venue to exchange and analyze model representations	• Produces a diversity of models and processes that each contribute to the main objectives • Does not produce an aggregate model • Distinct diversity is gained through the use of many models and ways of understanding • First, send, third person critical reflection • Dialectical confrontations
GPM	• Participation used to increase social relevance, validity, and actionability of research outcomes	• Maintaining the flexibility to adapt to constraints of problem, sector, and modeling tool kits • Use of an assortment of tools to have participants create formalizations of knowledge

Discussion

By inspecting the network graph, detected communities, and top degree papers in the PM core some generalizations can be made about the content of the different sub-fields of PM.

Group 0 represents a small cluster of documents written in the mid to late 2000s representing 14% of the documents. This group is dominated by an approach to PM called Mediated Modeling. Mediated Modeling (MM) is an application of GMB aimed especially at building consensus and conflict resolution in social-environmental management issues. The approach uses visually oriented system dynamics modeling software to iteratively and collaboratively construct a model (or models) of a system in which conflict about alternative policy or management decisions is existing or anticipated (Van den Belt, 2004). Its conflict mediation approach prescribes a structured engagement attuned to disagreement and utilizing explicit representation of models to represent and understand perceived conflict. This orientation necessitates the inclusion of processes of deep reflective process and constructive dialog to address and remove tension and includes momentum towards acting in difficult situations.

MM finds its participatory lineage in the design-oriented action research field and uses an action-reflection cycle to understand the MM process as it is initiated and proceeds with each group. MM pulls from Zuber-Skerrit (1992)'s CRASP framing of design-oriented action research, in which "Critical collaborative enquiry by reflective practitioners, who are Accountable in making the results of their enquiry public, Self-evaluative of their practice, and engaged in Participative problem solving and continuing professional development."

Group 1 is the largest group in the network and contains 50.35% of documents, all of which are from journals dealing with ecology, environmental management, or socio-environmental issues. Due to its larger breadth, it is more difficult to draw specifics, therefore we can consider it the Generalized Environmental Modeling group. GEM is situated more fully in sustainability science and ecological modeling than the other strands, and (in some cases) shares some of the formalized methodologies of GMB and ecological economic approaches (Gray et al. 2018; Naivina et al., 2012; Voinov et al. 2018). Often, GEM is a tool for adaptive management and adaptive co-management. This strand does not share a consensus in how participation is framed, though some authors have attempted to clarify how their processes work while maintaining the flexibility to adapt to constraints of problem, sector, and modeling tool-kits. Voinov & Bousquet (2010) describe GPM as the use of an assortment of tools to have participants create formalizations of knowledge. These formalizations (or models) can take the form of collective diagrams, rich pictures, or individual representations of mental models. Beyond representation, GPM may use participation to inform or interact with simulation models, and graphically represent a distributional understanding of populations under high uncertainty using local or indigenous knowledge.

Group 2 is the smallest group representing only 5% of the documents in the network and seems to be dominated by documents describing agent-based modeling and role-playing games oriented towards environmental decision making. Documents in this group seem to be associated with the Companion Modeling (ComMod) approach associated with researchers with the Agricultural Research for Development Agency (CIRAD) in France. The approach requires crossing disciplinary boundaries and views modeling as an intermediary object to facilitate collective and interdisciplinary thought (Barreteau, Bots, & Daniell, 2009; Kelly et al., 2013). This approach is novel in that it requires processes for understanding, confrontation, and shared analysis. In describing this posture, architects of the approach stress that that modelers discard all assumptions backing models after each interaction, to have no a priori implicit hypothesis, and to pay critical attention to issues and processes for validation.

ComMod is described as having two main objectives: Understanding complex environments, and to support collective decision-making processes. They base their work in iterative fieldwork – modeling – simulation cycle that produces a diversity of models and processes that each contribute to the main objectives.

Group 3 represents 31% of the network and can be thought of as Group Model

Building, an approach to modeling with stakeholders that originates in the 1980s from collaborative work by researchers in the Netherlands and the SUNY Albany system dynamics group (Eskinasi, Rouwette, & Vennix, 2009; Richardson & Andersen, 1995; Rouwette, Vennix, & Van Mullekom, 2002; Vennix, 1999). GMB builds off of early work in system dynamics and client-based modeling (John D Sterman, 1992). GMB is one of the first facilitated processes developed and systematically studied that looks at the effects of stakeholder involvement in the development, parameterizing, and scenario testing of (mostly system dynamics) models. The larger methodology, however, has been used with agent-based-modeling, concept mapping, network simulations, and a variety of combinations of integrated modeling. The method, though flexible and amenable to many contexts, finds its roots in the business and organizational behavior literature.

Vennix (1999) outlines GMB as a practice of involving stakeholders in the modeling practice that introduces social dynamics that can affect the model quality, stakeholder buy-in, and the likelihood that actions are taken based on modeling insights. Richardson and Anderson (1995), also developers of GMB, distinguish their approach in narrower terms, as a process with "the intent to involve a relatively large client group in the business of model formulation, not just conceptualization" (Richardson and Anderson,1995). GMB is united in that it employs structured processes that involve the use of facilitation scripts to illicit causal system-level understanding from stakeholders (Andersen & Richardson, 1997; Hovmand et al., 2012). This design choice is to increase the empirical and testable nature of the model building process, with an understanding that the social dimensions of model building have an impact on the resulting models and insights(Hovmand et al., 2012). Also, GMB largely focuses on top down modeling and documenting and uncovering the presence of feedback loops, and attempts to come to group consensus about system structure.

Also, within Group 3 we find Community-Based System Dynamics (CBSDM). CBSDM is an approach to GMB that provides a methodological framing rooted in the literature of Community-Based Participatory Action Research. The developers of this approach provide a highly structured and community-centered methodology to GMB that emphasizes long-standing community partnerships and community ownership of models (Hovmand, 2010.). It diverges from GMB, in its purpose of "involving participants to create a community of practice around a model that can be used to design innovations that the community will advocate for and implement" (Hovmand, 2010. p. 26). The processes of CBSD are prescriptive beyond general modeling of GMB to provide tools to define the community clearly, and places participants in the role of researcher, modeler, and interpreter of modeling results and process. Rooted in action research, this approach is ontologically and epistemologically tied to how the community is framing the problem.

Conclusion

The findings from this analysis provide a novel understanding of the field of participatory modeling and contributes a broader understanding about the nuances in the different ways modelers approach practice. By identifying PM subfields through quantitative means we contribute to the PM review literature (van Bruggen, Nikolic, & Kwakkel, 2019; Voinov & Bousquet, 2010; Voinov et al., 2018) while integrating across disciplinary and modeling frameworks.

PM often requires an interdisciplinary understanding of the problem the modelers are investigating. By this same principle, modelers could benefit from learning from other literatures and traditions of PM. This study shows that there are divergences in the specificity and formal processes used in participatory modeling and the practices of one tradition may enhance the practice in other traditions. For instance, though the subfields of environmental modeling and public and community health modeling have developed within specific traditions, there is significant overlaps in the type of problems being modeled and the role of models play in system scale decision making under uncertainty.

This work provides a new cross-tradition framework for considering PM as a

Chapter 3 Connectivity and Social-Ecological Resilience

Introduction

Connectivity is an important component in the heuristic of SES Resilience; however, it is difficult to measure or approximate. Using Stakeholder Mapping and Small World measures can give practical insight into what this means for food systems. In this paper, we review the concept of connectivity and how it has been used in SES resilience and offer the measure of Small World effect to understand one aspect of connectivity that has been overlooked in empirical studies. We then present a case study using this measure to understand the SES resilience of an urban food system. We then contrast the SME with robustness measures and propose the creation of a metric to articulate the tradeoffs between robustness and small worldliness.

The concept of resilience has multiple meanings related to the scholarship of sustainability. Originating in the field of ecology (Holling, 1973)and now extending to many interdisciplinary scholarship branches, resilience is universally seen as a property of a system. Quinland et al. (2015) outline three definitions from the ecological literature. These are: engineering resilience –or the speed a system returns to a (particular or singular) equilibrium after experiencing a shock; ecological resilience—or the magnitude of disturbance that a system can absorb before shifting to an alternative regime (multiple equilibria); and social-ecological resilience which extends the ecological definition to include the amount of disturbance that a system can absorb and remain within a domain of attraction, the capacity of a system to learn and adapt, and the degree to which a system is self-organizing (Carpenter et al., 2001; Quinland et al., 2015).

As a system property, social-ecological resilience offers a rigorous appreciation for the emergent and complex properties of social-ecological systems (Berkes & Folke, 1998; Westley et al., 2011) Folke et al. (2010) illustrate that aspects of social-ecological systems inform this definition of resilience, namely persistence, adaptability, and transformability. Adaptability refers to any social-ecological system's capacity to adjust to or respond to changes in both exogenous drivers and endogenous processes and remain within its current stability domain. Transformability, however, is the capacity to create new stability regimes once critical thresholds are crossed. The key to these features is the fundamental property of complex systems to self-organize.

Connectivity is a construct used in social-ecological resilience to refer to the strength and structure in which resources, actors, or species interact across geographies, ecosystems, and social domains(Biggs, Schlüter, & Schoon, 2015). It has been theorized that connectivity, operating across multiple spatial and temporal scales, can increase resilience to the provisioning of ecosystem services, system governance, and to facilitate recovery after a disturbance or shock (Bodin & Prell, 2011; Colding & Barthel, 2013; Janssen et al., 2006). However, it has been observed that highly connected systems increase the potential for disturbances to spread and that densely connected systems lose the ability to adapt and appear "locked" into their current system structure (Bodin & Crona, 2009; Bodin & Prell, 2011; Janssen et al., 2006). This tension exists because the relationship between resilience and connectivity is complex and multi-dimensional.

Network analysis has been proposed as a method to understand the structure of SES and to assess the level at which connectivity is responsible for specific outcomes. A network approach to SES can provide a way to compare cases with a topology of network properties relevant to SES. Though empirical studies on the effect of connectivity on SES resilience are increasing in number, they are still quite rare. Bodin and Prell (2011) show how densely connected networks facilitate the governance of ecological resources. Bodin and Noreberg (2005) show how densely connected networks lower diversity of management strategies increasing risk.

Janssen et al. (2006) describe two dimensions of connectivity in its importance to SES governance and resilience. First, they describe connectivity as primarily a function of network density, or the total number of connections in a network divided by the total possible connections a network could potentially have. Reachability or the ability for any node to reach another node in a network is the second dimension. Like many network scientists before them, they show how these two dimensions are independent, and it is possible to have high density and low reachability and vice versa.

In this study, we explore how extending these dimensions further to include small-world effects can yield insights into a network's ability to foster social learning, innovation, and adaptive capacity. Our analysis will contribute to the growing literature on networks and SES resilience and will further our empirical understanding of how small-world networks can explain resilience outcomes.

Small Worlds

The concept of small-world networks can be critical to understanding how SES structure is responsible for outcomes essential to resilience. Sometimes referred to as the Small World Effect (SWE), based on the inherent characteristics and outcomes that these structures enable, we argue that it is related to the concepts of adaptive capacity, innovation, and creative problem solving all vital to understanding how connectivity operates within SES.

Small-world networks are in a class of mathematical models in network science that describe topographical patterns observed in various networks (Uzzi, 2014; Watts & Strogatz, 1998). The literature on the small-world phenomenon is varied and includes a diverse collection of popular work. Milgram (1967) was the first to study communication chains and discovered that even in extreme geographic and social distances, strangers are connected by no more than six degrees of separation (Milgram, 1967). Further described by Watts and Strogatz (1998) as networks that are "highly clustered, like regular lattices, yet have small characteristic path lengths" (Watts and Strogatz, 1998). This provides networks that allow for highly specialized clusters while simultaneously being able to reach or communicate with all parts of the network quickly and efficiently.

Small-world properties have been implicated in social capital studies, demonstrating both bonding and bridging capital (Inkpen & Tsang, 2005). Thus, small-world networks combine structures that support the close group bonding associated with local cooperation and trust, with broad reachability to transmit resources and information throughout the entire network effectively.

SWE can be an important indicator of a network's adaptive capacity. Writing about adaptation and adaptive capacities, Eakin et al. (2014) describe adaptation as being contextual and related to the specific capacities needed to act and respond to increasing vulnerability and climate risks. Eakin stresses that adaptation is necessary to "manage environmental variability" and that these actions are taken in the pursuit of meeting and enhancing human needs, speaking to the foresight, and intentionality of the actions taken (Eakin, Lemos, & Nelson, 2014). Here the capacities necessary for adaptation reflect the conditions that promote and reflect learning, experimentation and encourage innovative solutions (Berkes & Folke, 1998; Walker et al., 2002).

Stakeholder Mapping

Eckert and Vojnovic (2017) demonstrate how the path of many Midwest U.S. cities, disinvestment and decline, can lead to spatial disparities in characteristics of food system outcomes. They explain that these spatial disparities in cities like Flint, MI are associated with behavioral preferences, the availability of consumer choices, and the relative distance consumers travel for meals (Eckert & Vojnovic, 2017). However, residents and stakeholders of Flint, MI, exist in a dynamic culture of activism and experimentation around reimagining their food systems through collaborative community-based exploration. Like many social-cultural problems, redefining food environments is often considered community-centric systems change. Frameworks on community systems change have demonstrated the need for many stakeholders to work towards common goals across scales (Foster-Fishman & Watson, 2012). Understanding the diversity of these actors and how they are connected within the system can be a first step in organizing that knowledge towards collective action.

Stakeholder mapping is a tool to assess a social-ecological system's features by way of its connections and flows of resources. It falls into a long history of rapid appraisal methods developed to assess current and past conditions when baseline data is not available or too costly or difficult to collect (Chambers, 1994). Like many rapid appraisal methods, it relies on the experiential knowing of knowledge holders with unique information about the system. These methods and tools are designed to be deployed in the field settings, with low technology, and to capture accurate information. The technique also draws from Cognitive Social Structures (CSS), a network science approach that usually prompts individuals to describe their ego-networks and inform about perceived relationships between other actors (Brands, 2013).

Stakeholder mapping (SM) as a resilience assessment method has been detailed in the Resilience Assessment manual and used in various cases to understand the structure of social-ecological systems (Resilience Alliance, 2010). A modified version of this protocol was developed to understand the flow of resources and connectivity in the Flint food security system. This protocol was designed to include food system actors and experts from different sectors of the food system using the conceptualization by (Ericksen, 2008).

(SM) exercises were conducted with stakeholder groups representing the Flint food system (Stakeholder Mapping Procedure in Appendix). SM was conducted with ten groups in Flint representing consumers, the supplemental and emergency food system, neighborhood leaders, food processing, governance, and philanthropic organizations. In total, 64 individuals participated in the SM exercises. This is a slight departure from the Ericksen (2008) conceptualization but focuses on what community stakeholders view as the central components of their localized context. Ericksen (2008) states that food systems "incorporate multiple and complex environmental, social, political, and economic determinants encompassing availability, access, and utilization" which exist along different temporal, spatial and governance levels (Ericksen 2008, p 234). The decision to focus on the localized context of food security for residents of Flint, is not a reconceptualization of the food system, but focuses on components that are accessed and understood by participants.

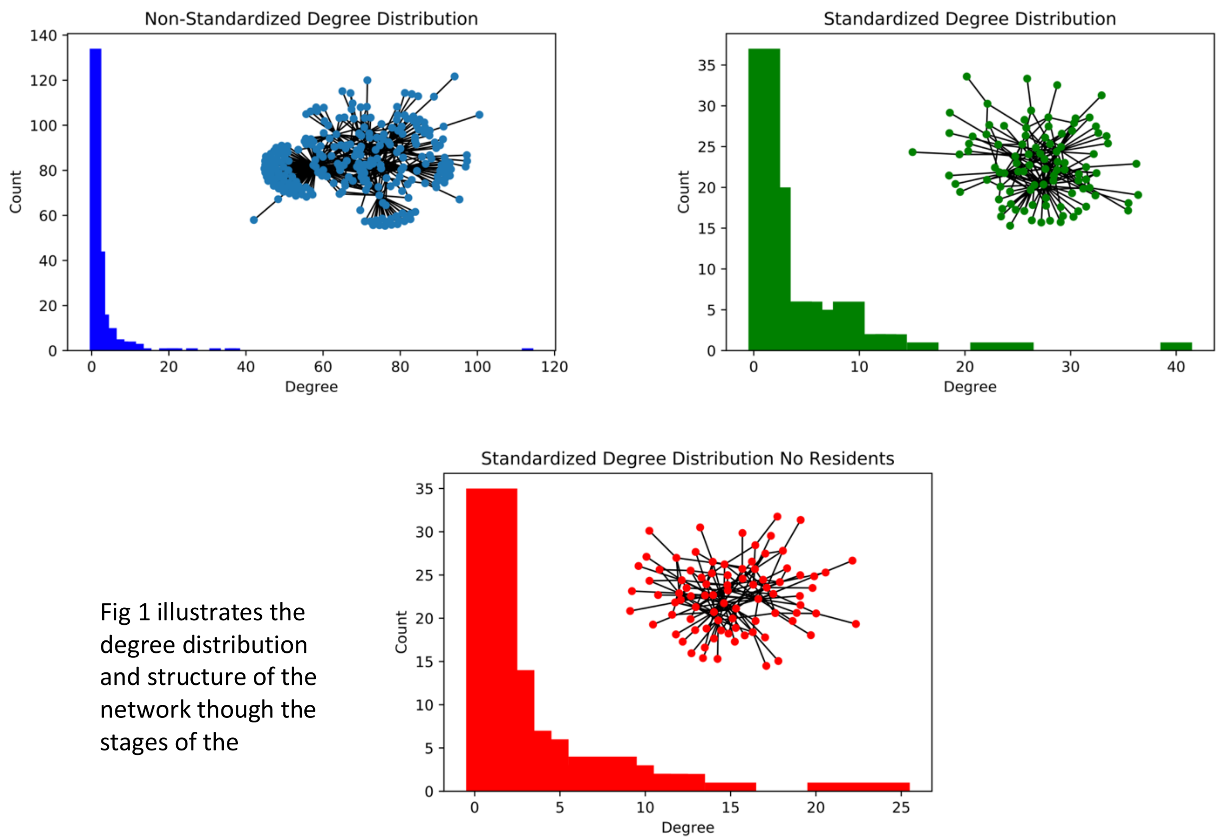
The SM workshops focused on connections in the food system, as defined as flows of material resources, or information about the food system, specifically aspects of the food system dealing directly with resident food security. Therefore, from here forward we will refer to this network as the food security governance network.

Participants were asked to first free-list food system actors on to post-it notes individually. Then the post-it notes were aggregated on a central board for combining redundancies and sorting by theme. Participants were then asked to indicate the resource flows between food system actors, indicated by directed edges. For instance, if participants know that or perceive that a local food pantry receives information about food need from a specific church group, they would draw a line indicating a flow. The resulting diagrams from the individual workshops were then digitized using Kumu (Kumu, 2020) software and then translated into adjacent matrices for further analysis.

Translating Stakeholder Maps to Networks

Like all network assessment methods, SM is sensitive to missing data, especially the edges that can drastically change the network's topographic characteristics(Wasserman & Faust, 1994). To address this limitation, we aggregated the individual SM diagrams into a single network, which may address the discrepancies and limited network knowledge of individual workshops, similar to consensus based cognitive social structures (Brands, 2013). Node standardization procedures were developed to construct the aggregated network. The primary research aim was to understand the localized food system structure, so we standardized it to the closest meaningful unit for grocery stores, restaurants, and organizational and governance actors. This process was essential to reduce noise in the data while preserving the structural integrity of the network. Figure 1 compares the nonstandardized aggregated network to the standardized aggregated network. What is evident in the sociogram and degree distribution is that the unstandardized network has many peripheral nodes with a degree of 1. This may be an artifact of the data collection process because consumers receive material resources (food, namely) from many different restaurants and grocery stores. However, participants were less likely to know of connections between individual restaurants or grocery stores. However, they were aware of broader connections, such as a connection from "grocery stores" to the food bank. This example further illustrates the choice to collapse nodes instead of extending edges to all grocery stores prevents adding many more edges that may overstate an actor's participation in programs or relationships.

Figure 3-1 Comparing Degree Distributions Across Networks



Furthermore, the SM protocol largely had "consumers" start with a central node "resident"/"me"/"consumer". This resulted in a highly centralized node, with a degree count double that of the next highest degree node. This also created a fully connected network through the individual. Though it is important to understand the consumer role in the food system, this created an artifact in the network where consumers lay on the shortest path between organizations, nonprofits, and governance actors and were largely artificial. For instance, though it makes sense to combine instances of "The Food Bank" from different workshops, as the intended meaning of this node is the same, the presence of "resident"/"me"/" consumer" does not represent a single entity or node. To address this, we removed the aggregated consumer node from the network, while leaving representations of specific consumer or resident groups deemed vulnerable (ie, seniors, Latin-X, children). This largely allows us to view the network as the social-ecological governance network of the food system, and more closely analyze its structures, clustering, and capacities without distortion created by this artifact.

Because this network represents the aggregated diagram of multiple workshops, we had to deal with parallel edges. Parallel edges or multiple edges between two nodes are treated differently in networks to yield different insights into the properties of a network, depending on the meaning of, or reason for the parallel edge (Wasserman & Faust, 1994). For instance, in a citation network, multiple edges mean multiple citations of a given author to another. These can be summed, averaged, or transformed to yield some metric of the strength of a particular edge. In aggregated SMs, parallel edges indicate that a particular edge was identified in multiple workshops and may give insight into the validity of a particular edge. However, establishing this metric of edge validation is beyond the scope of this research but could be a future direction in SM following similar research in CSS in consensus representations (Brands, 2013; Freeman, Romney, & Freeman, 1987; J. W. Neal, 2008). For our purposes, the minimum edge value is used. It creates a binary value indicating whether an edge is present (1) or not present (0) and provides the minimum threshold for a tie to be represented.

Analytical Methods

To conduct our analysis, we used the networkx v 2.3 package (Hagberg, Schult, & Swart, 2008) in the Python 3.7 computing environment (Van Rossum & Drake, 2009) to calculate all network measures. Our analysis is mostly descriptive and focuses on examining networks' structural characteristics to understand connectivity and SES resilience. Janssen et al. (2006) describe three important network metrics for understanding a system's social-ecological resilience. We have calculated these metrics using the following formulas.

We calculated the following descriptive statistics for the network: radius, diameter, density, degree centralization, average clustering coefficient, and average path length. We calculated standard centrality scores (degree centrality, betweenness centrality, eigenvector centrality, and closeness centrality), which will enable us to consider localized properties of the network (Wasserman & Faust, 1994). Density is the most straightforward measure of connectivity and represents the fraction of observed ties over the maximum number of possible ties (Wasserman & Faust, 1994). The average clustering coefficient is a measure of triadic closure. It is calculated by averaging the local clustering of each node and the fraction of that node's connected neighbors (Wasserman & Faust, 1994). Average path-length is the mean number of edges on the geodesic path between any two nodes in the network. The diameter of a network is the maximum geodesic distance in the network. It gives the number of steps that are sufficient to go from one node to any other node. A small diameter means that it is possible to traverse the entire network in only a few steps.

There are multiple ways to compute small world quotients provided in the literature (Z. P. Neal, 2015). For computing the small-world quotient we used Omega as it appropriately compares the clustering coefficient to a lattice-based reference and the mean path length against a random graph reference. It offers a fixed scale for comparison across other networks (Watts & Strogatz, 1998).

$$\omega = \frac{Lr}{L} - \frac{C}{Cl}$$

C and *L* are the average clustering coefficient and average shortest path length of the network. *Lr* and *Cl* are the average shortest path length and average clustering coefficient of an equivalent lattice graph. This coefficient ranges between -1 and 1. Values close to 0 mean that the grap features small-world characteristics. Values close to -1 mean that the network has a lattice shape, whereas values close to 1 means the network resembles a random graph.

The equivalent networks used to calculate *Lr* and *Cl* were created using networkx reference network generator. The metrics *Lr* and *Cl* were sampled from 10,000 respective equivalent lattice and random networks. We used the default setting for the rewiring coefficient to be consistent with other works (Telesford, Joyce, Hayasaka, Burdette, & Laurienti, 2011).

Results

Table 2 shows the general descriptive for the SM network. Figure 4 shows the degree distribution of the aggregated, minimum edge value network with residents removed.

The food security governance network contains 87 nodes and 174 edges. It has a density of 0.047, radius of 4 and diameter of 6. The observed average path length is 3.060 and is very similar to the expected average path length of 3.107. The observed average clustering of 0.195, lower than the expected average clustering of 0.315. The SMQ is 0.397. As noted earlier, the SMQ is scaled between -1 and 1. A score around 0 indicates a perfect small-world structure. Scores closer to one indicate that the network resembles more of a random structure and scores closer to -1 a structure similar to a lattice network. The network has small-world features but tends towards the random network side of the scale.

Table 3-1 Descriptive Statistics & Small-World Quotient

Descriptive Statistics and Small-World Quotient	
	Major Component
Nodes	87.00
Edges	174.00
Diameter	6.00
Density	0.05
Radius	4.00
Average Shortest Path	3.06
Average Clustering	0.19
Expected Average Shortest Path	3.11
Expected Average Clustering	0.32
Small World Quotient	**0.40**

Figure 3-2 Social Ecological Governance Network

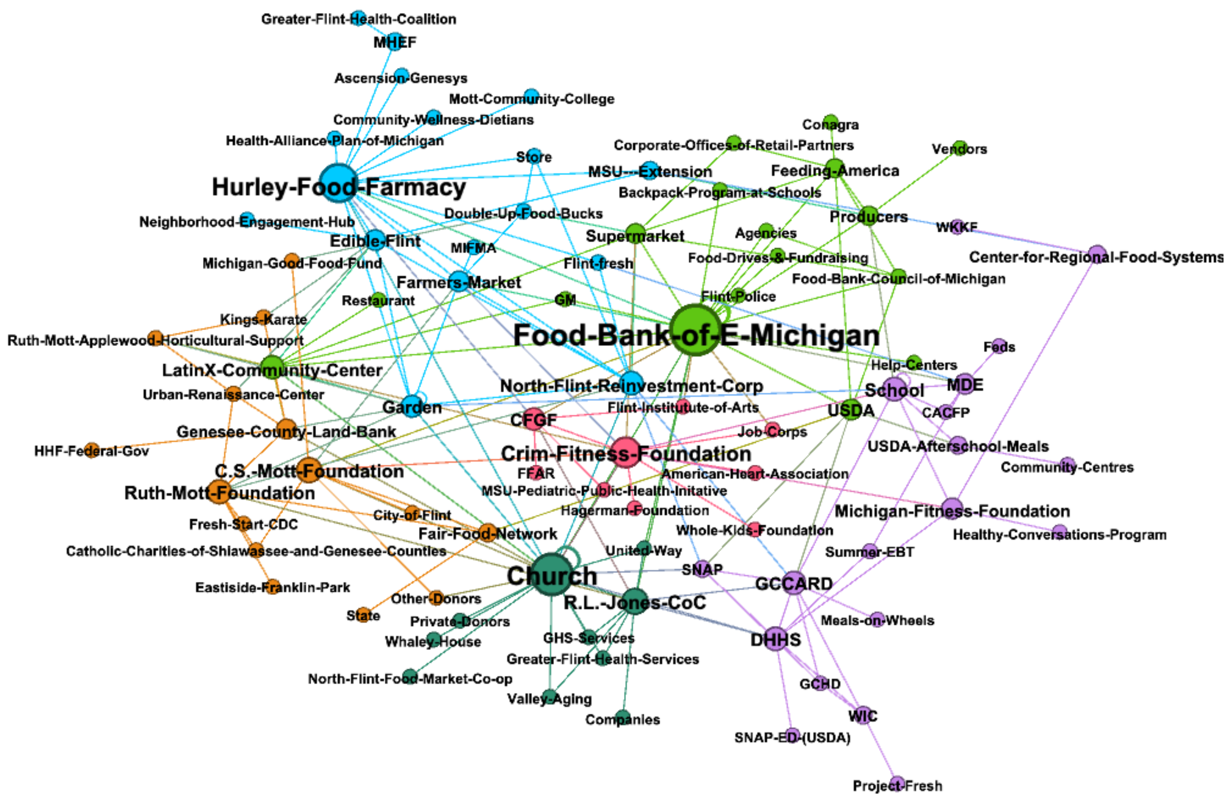


Fig. 2 Food Security Governance Network using forced spring layout. Node size is based on relative betweenness centrality. Color is modularity group.

Discussion

The SWQ for the network is 0.397, meaning it has some features and characteristics of small-world networks but also tends towards a random network. We can turn to other descriptive statistics to explain this outcome. The network has a relatively small average path length of around 3 steps and a diameter of 6. This means that the reachability of the network is quite high. Information can travel through this network with relative ease though there are peripheral outliers, it resembles the average path length of the expected random network equivalent. Recalling that the SWQ is a ratio of ratios, it compares the average path length of the network to a random network and compares the average clustering to that of a lattice network. The network has a low average clustering of 0.19 compared to the expected average clustering of an equivalent lattice network, which is 0.315. This low clustering could be due to the need for the food security governance network actors to act in unison while not specializing in any aspect of the food security system. This clustering is often credited for the development of trust, reciprocity, and specialized modes of action. This is not to say that the network does not have clustering, but it is more integrated across the groups which can have positive effects for sharing information and efficiency.

The degree distribution can also explain why this network tends to have low small-world features. There are highly central actors in the network that most nodes must communicate through or with to take any actions. These high degree actors can be thought of as gatekeepers or boundary spanners. In the case of gatekeeping, these actors may be inhibiting the development of specialized groups or clusters by controlling the flow of resources making the network highly dependent on the actions of these high degree nodes (Bodin & Prell, 2011).

This is not to discount the small world features of this network which is still agile and able to adapt, innovate, and change focus to work on specific issues due to the high global efficiency of the network. However, the capacity to do so could be highly reliant on or directed by the most central nodes.

The lack of clustering could also be an artifact of how the SM protocol was developed. The SM protocol prescribed that workshops be conducted with stakeholders with similar roles in the food security system. The workshops were designed to capture expertise in the localized networks of the specific groups that the participants represented. It was expected that similar stakeholder grouping would provide more accurate information about the group's mental models of the network, but be biased towards their connections and expertise (like in CSS). However, it could be the case that these inter-group connections were underrepresented. These actors may exchange ideas, information, and even collaborate on projects within the food security system, but because they were all in the room together, the ties may have been implied.

Further research into the effect of workshop group homogeneity on SM accuracy is needed, especially if the within-group ties lack. In our analysis of community detection, we did not find tight clusters around similar types of actors that would be unexpected. The largest modularity or group contained actors from all sectors of the food security system. Future work could compare workshop diagrams to one another to find if the group composition and diversity affect the accuracy of the modeled network, similar to how CSS has been analyzed in Freeman et al. (2013), Neal (2008) and Brands (2013) (Brands, 2013; Freeman et al., 1987; J. W. Neal, 2008).

Conclusion

The purpose of this work was two-fold. One to examine how outcomes of SM can be analyzed quantitatively as networks. Secondly, to demonstrate how the SWQ can be used to understand aspects of SES resilience, namely adaptive capacity and robustness. The resulting aggregate network of the f food security governance network has small-world features but has lower clustering than expected in a small-world graph. We discussed how this graph may be efficient at transmitting information and resources throughout the network, but that there may be a lacking component of trust and intergroup connectivity.

Specifically, information can travel through this food security network with relative ease. When faced with a shock this efficient information spread among different actors is vitally important. Different actors are also likely aware of similar information and each other's actions. However, due to the lack of clustering in the network, trying to coordinate these efforts may be difficult (Lawlor & Neal, 2016). Furthermore, consensus on actions and other governance decisions may be costly to implement (Chavis, 2001). This could lead to disagreement about how to respond to shocks or even redundant, uncoordinated actions (J. Lawlor, Metta, & Neal, 2020).

This food security governance network would likely benefit from a network intervention in the form of a coordinating council, food policy council, or coalition effort to build intergroup connections and trust (Chavis, 2001; Schiff, 2008) . These types of entities can assist in distributing power and build coordinating capacity (Harper, Shattuck, Holt-Giménez, Alkon, & Lambrick, 2009).

Methodologically this paper contributes a novel way to compare the adaptive capacity of SES network structures going further than prior works (Bodin, Ramirez-Sanchez, Ernstson, & Prell, 2011; Janssen et al., 2006). It also contributes a process of using a mixed-methods, rapid approach to collecting and analyzing network structure in complex social-ecological settings.

Chapter 4 Translating Narratives into Archetypes

Introduction

The topic of using system archetypes in the modeling process has been raised repeatedly in the system dynamics literature. Many authors have pointed to the communication and implementation stages of the modeling process in their evaluation of archetypes' usefulness. However, few works detail the exact process used for identifying the archetypes. In this paper, we examine explicitly how archetypes can be identified in qualitative data and how they can be used as a boundary concept to translate modeling concepts. We then extend on Wolstenholme's (2003) work on archetypes and Kim and Anderson's (1998) framework for analyzing qualitative data in model building by demonstrating a qualitative coding schema adapted from Wolstenholme's definition of totally generic systems archetypes (Wolstenholme, 2003). We demonstrate the usefulness of this process by using focus group data that was designed to elicit future visions of the food system. We illustrate how this process can retain the narrative form that the data originated while being useful enough to provide generic modeling structures to the modeler. By increasing the narrative's connectedness to the model, we will show how this can enhance the modeling process and give specific insights into systems thinking pedagogy and practice.

Archetypes

Archetypes are system structures that produce characteristic patterns of behavior. System archetypes are a well-documented tool for communicating the structure and behavior of systems and have been applied across various contexts (Kim & Anderson, 1998; Senge, 2006)They are useful both as a communication heuristic and as an initial step towards building a model that reflects a system of interest. Kim and Anderson (1998) describe system archetypes as recurring narratives or stories that help build an understanding of system structure by being attuned to systems' behavior over time. Like many in the field of system dynamics (Newell, 2012; Senge, 2006; E. Wolstenholme, 2004), Kim and Anderson (1998) find that archetypal structures promote systems thinking by creating a communicative environment to express intuitive observations of familiar systems.

Newell (2012) points out the value of metaphors in establishing shared understanding. He argues that metaphors must be easily understood across various knowledge backgrounds and that system archetypes can be a particularly powerful metaphor because they are simple, easily understood, and provide relevant representations of systems. This is critical when communicating in a community context around systems and system behavior, for example, when engaged in community-based modeling.

There have been divergences in the systems literature on what constitutes a systems archetype (Lane & Smart, 1996; Paich, 1985)and how many genuinely exist (Senge 1990, Wolstenholme and Coyle, 1983; Kim, 1992). Meadows (2008) building on early work of Forrester (1968), Goodman, Kemeny, and Roberts (1994) and Senge (1990) present eight archetypes for learning systems thinking. These eight referred to as semi-generic archetypes by Wolstenholme (2003) and here throughout, are quite descriptive in the problem space one might observe and how stakeholders may experience an archetype but are arguably imprecise in their description of the underlying system structure.

Writing on the importance of boundary setting, Wolstenholme (2003) identified four generic two-loop archetypes (Underachievement, Out of Control, Relative Achievement, Relative Control) to address complex intra and inter-organizational challenges. Wolstenholme argues that these four archetypes represent the truly generic structures that capture the system's observed dynamic behavior. These generic two-loop archetypes build off of the isometric properties of feedback loop polarity and demonstrate how two feedback loops in different combinations can create different behavior. Wolstenholme provides the fundamental characteristics of a two-loop archetype. First, it is composed of an intended consequence (ic) feedback loop representing the initial action of an organization or group. Secondly, it contains an unintended consequence (uc) feedback loop resulting from the reaction from within/or outside the organization. Thirdly, it contains a delay before the uc manifests or is known. Furthermore, that there are organizational boundaries that mask the uc from actors initiating the ic action.

These characteristics allow for a precise description of the structure of an archetype. They can help identify the proper archetypes and solutions that may be useful in addressing the problem. In the following sections, we will show how we adapted the Wolstenholme Generic Archetype Criteria to create a qualitative data analysis scheme to identify archetypes in qualitative focus group data. Then we will compare the Wolstenholme Generic Archetypes to the semi-generic archetypes as a framework for extracting and analyzing qualitative data. We will then demonstrate how the process can retain the narrative form of the collected data and aid in multiple steps of the modeling process.

Qualitative Research and SD

The foundational literature on creating system dynamics models has stressed the iterative processes necessary to create, test, and evaluate models. Part of the iterative process of building models has been the conversion of often rich qualitative data into numerical models that can be used for decision support through the use of simulation modeling. Often this rich qualitative data has been described as living within the minds of system experts or managers, often referred to as mental models. These mental models have been recognized as a vital source of system information.

Forrester, Sterman, and Vennix all discuss the importance of capturing these expert mental models in different modeling stages (Forrester, 1991; J.D. Sterman, 2001; Vennix, 1999). However, guidance on how to analyze and interpret these data has lacked in the foundational literature. In the next sections of this paper, I will review the literature that explains the integration of qualitative data into system dynamics models.

Luna-Reyes and Andersen (2003) establish that there is an agreement in the field of system dynamics that qualitative data is vital to the development of models. They stress that the field lacks rich documentation of how these processes should be integrated, obtained, and analyzed when used to build quantitative models(Luna-Reyes & Andersen, 2003). They claim that this creates a gap between the problem modeled and the model of the problem. They document that meta-physical variables are challenging to measure and create difficulty integrating them into quantified models. They believe that the development of qualitative system dynamics practice (Wolstenholme 1990) is a reaction to this difficulty and a desire to preserve the integrity of these data. Without engaging in the debate, they argue that understanding qualitative social science could enhance the modeling process across all stages.

Luna-Reyes and Andersen (2003) outline the main areas of qualitative social science methods and illustrate how these methods can be used in system dynamics modeling. They then turn to grounded theory to collect, extract, and analyze qualitative data to build, conceptualize, and formulate model representations.

Turner, Kim, and Anderson (2013) demonstrate using grounded theory and textual data to create shared representations of a group's mental model by analyzing purposive focus group data to create diagrams of the system in question. Kim and Anderson (2012) use grounded theory and purposive text data to demonstrate a technique to map mental models as causal loop diagrams. Building of this prior work Eker and Zimmerman (2016) introduce an approach that synthesizes qualitative techniques with a focus on causal relationships, creating simplified maps, and maintains links to the data and causal map choices.

All of these scholars have also stressed how costly and time-intensive the process can be. They use grounded theory as a way to build a theory with the data. One aspect of qualitative data that has not been demonstrated in SD processes well, but is likely used, is the use of directed qualitative coding. This involves using a theoretical framework from the beginning, as opposed to the in vivo method of grounded theory. This can allow coders to direct their attention and efforts to understand generic structures in the narratives of experts, and code across observation to aggregate and merge an understanding of the dynamics at play.

In this paper, we will demonstrate the use of a directed coding procedure that focuses on the generic structures of systems, or system archetypes, to analyze data in the conceptual and formalization of the model. We will first review the system archetype literature and show how archetypes can bridge the gap from purely qualitative representations to rapid prototyping of formalized system dynamics models.

Data Collection

The analysis for this paper builds on existing system dynamics research using qualitative data to construct models and maps (Luna-Reyes and Anderson 2003, Kim, 2007) and extends it by creating a coding scheme that aids in the identification of generic feedback structures and system archetypes. The codebook allows for directed qualitative content analysis and the development of the system's theory and models based on the purposive text data from focus groups. The categories for the codebook represent necessary components of a system archetype, but the codes within the categories are generated inductively through the emergence of essential variables and concepts.

A food system conceptualization informed the data collection design from Ericksen et al. (2008). The Visioning Protocol is found in the Appendix. The intention was to engage with knowledge holders from a variety of perspectives: Consumers, Producers, Emergency Food Delivery, Philanthropy, and Governance sectors. In total, seven workshops were conducted with these community knowledge holders, with two workshops dedicated to consumers, two to the emergency food sector, and one each for the philanthropy and governance sectors. Participation in focus groups ranged from 2 participants to 10 participants, in all representing 64 participants.

The focus groups were designed to follow a visioning protocol, asking participants to share their experiences with the past, present, and future of the food system in their community. Because the data was collected as a visioning exercise, the data is not explicitly about system dynamics or using known scripts from Group Model Building (Andersen & Richardson, 1997; Hovmand et al., 2012). However, the visioning protocol does prompt discussion about the dynamics of the food system over time. This data is relevant for our task as it demonstrates the strength of the coding process to identify system archetypes to data that is not specifically designed to elicit them. It also provides case examples of when there was not enough data to determine an archetype or causal structure, allowing us to reflect on the development of future facilitation scripts aimed specifically at eliciting archetypical structures from knowledge holders.

Data Extraction

The focus group audio was transcribed into verbatim text data. It was first necessary to scope and create a codebook to guide the extraction and initial review of the qualitative data. Working with guidance from Turner, Kim and Anderson (2013), in the use of social science techniques in system dynamics modeling, it is clear the goal of this research process is based on a grounded theory approach, with the intended purpose of constructing causal theories from the data at hand.

We also wanted to utilize system archetypes as a boundary concept to link the original data to causal models or theories. For this, we utilized the generic structures identified by Wolstenholme (2003). These structures have precise components that guide the modeler and participant in the construction and identification of the archetype involved in the described dynamic behavior. Wolstenholme (2003) also provides criteria for identifying archetypes, as noted in the previous section.

The two coders (first and second authors, respectively) then read and re-read the transcripts to identify instances of dynamic behavior over time. The full quote containing the dynamic behavior was then the unit of analysis that we applied our broad coding scheme.

Major Stocks

The data were coded for the potential of major stocks that may be important to capture in the final model

Central Actors

System dynamics always include actors and decision-makers. Coders were instructed to extract any information about central actors mentioned or inferred from the data.

Behavior

In some cases, participants describe the dynamics of important stocks overtime. Behavior was captured as both graphs drawn by the coders and the participant's descriptive language.

Sectors and System Boundaries

As Wolstenholme discusses, system boundaries often mask the effects of unintended consequences in a system. It was important for the data extraction to include system boundaries or sectors when necessary or apparent. Boundaries were only included if it was explicitly mentioned or flagged for follow up with experts with unique insights into the system in question

Structure

The coders also needed to infer through careful analysis, what structure led to this outcome. These are represented as dynamic hypothesis/reference modes or archetypes. The coders used the components of Wolstenholme archetypes to guide this extraction.

Problem

This was lifted directly from the transcript and referred to something in the system that is either not working, underperforming, working well, or in need of elimination.

Action

Something that actors in the system have tried as a way to remedy the problem

Intended Consequences

The expected outcome of the action

Unintended Consequences

The unexpected outcome of the action, often happening with delay or outside of the sectoral boundaries of the major actors conducting the action.

Delays

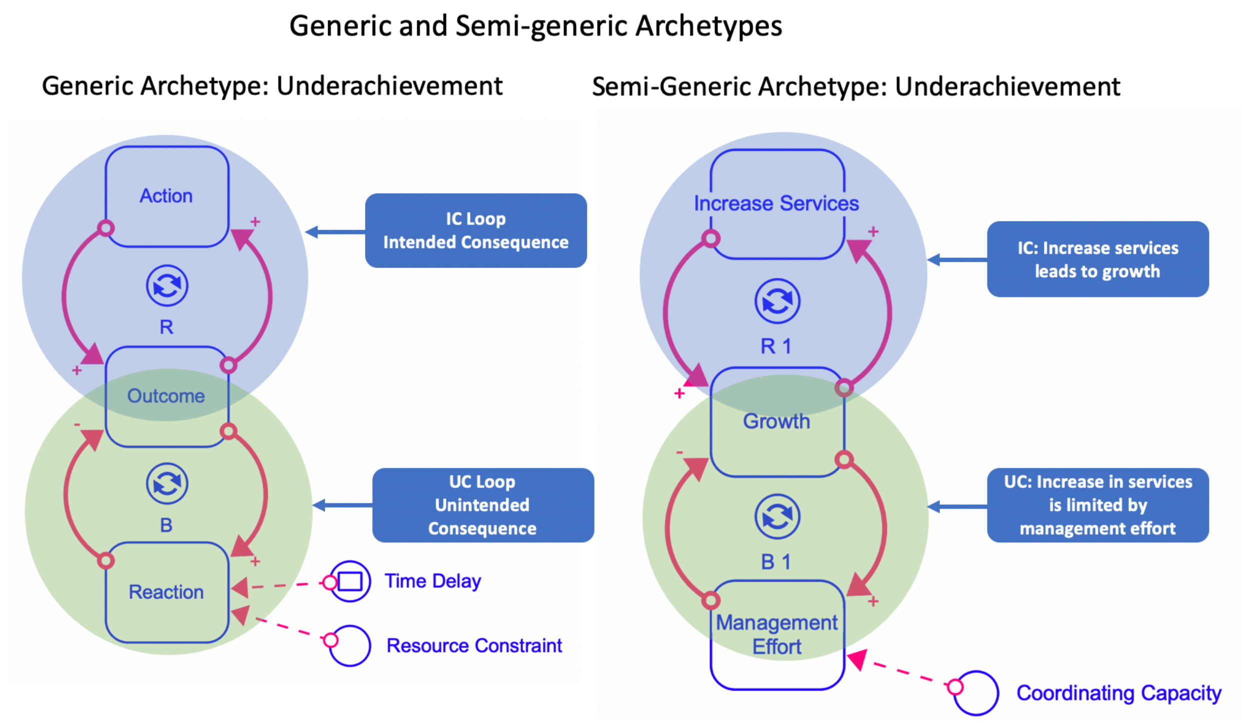
Delays could either be explicitly referenced in the text or inferred by the coder from the described system behavior

Feedback loops

Feedback loops were rarely referenced directly in the text but were inferred by the coders when there was language representing feedback. In facilitation or interview informed by a modeling process, we would expect this to be more explicitly represented in the data and more accessible to code/tag/flag.

Then the extracted texts were categorized into both a Wolstenholme and semi-generic archetype. Though in Wolstenholme (2003), it is shown that semi-generic archetypes map on to Wolstenholme generic archetypes, it was of interest for testing of communication strategies to identify both sets of characterizations. Archetypes were identified using Wolstenholme's characterization and by analyzing the cases across the extracted and inferred data. For instance, if the extracted data revealed a Problem of growth of a sector, with an Action of increased investment, and Intended Consequence of more services provided, and an Unintended Consequence of increased complexity and difficulty coordinating services, the archetype was identified as "Underachievement" as the generic and "Limits to Success" as the semi-generic archetype, as shown in Figure 1.

Figure 4-1 Comparing Generic and Semi-generic Archetypes



Finally, the extracted data were classified into categories of "It Worked," "It Did Not Work," and "Not an Archetype." These categories specifically refer to whether or not the archetype identification process was successful for these individual cases. These determinations were primarily based on there being enough data in the quote, or within the context of the focus group transcript to determine the archetype category. This final classification will allow for further analysis of what type of data was missing and how to design future workshops with archetype data in mind.

Each coder independently read and extracted data and met to discuss each instance of extracted text to gain consensus on the classification and categorical data. The open coding process within the categories was then classified into categories that fit the scale of a regional food system. For instance, in Actors, specific grocery stores or organizations were converted into standardized versions based on their scale of influence.

Descriptive Results

This section outlines the results of the coding process and the archetype analysis. It discusses the different archetypes identified in the data, gives examples of how the data was structured, and the archetypes identified.

There were over seven hours of transcribed audio. From those transcripts, 208 instances of dynamic behavior were identified and extracted for analysis. They deal with 70 stocks, 35 types of actors and contain examples of all generic and semi-generic archetypes. We were able to identify semi-generic archetypes for all instances and fully generic archetypes for 179. Table 3 illustrates the general descriptive results of the extracted data.

Table 4-1 Archetypes Descriptive Table

Archetypes Descriptive Table			
Classification	**Count**	**Semi Generic Archetypes**	
Almost Worked	17	**Out of Control**	**55**
It Worked!	184	Fixes That Fail	31
Not Archetype	2	Shifting the Burden	12
Grand Total	203	Seeking the Wrong Goal	8
		Eroding Goals	1
Generic Archetypes		Squeaky Wheel Gets	1
Out of Control	55	Accidental Foes	1
Relative Achievement	8	Rule Beating	1
Relative Control	12	**Relative Achievement**	**7**
Underachievement	93	Success to the Successful	7
Unknown	17	**Relative Control**	**12**
		Eroding Goals	11

Table 4-1 (cont'd)

Semi Generic Archetypes		Escalation	1
Limits to Growth	97	**Underachievement**	**93**
Fixes That Fail	32	Limits to Growth	93
Shifting the Burden	12	**Unknown**	**17**
Eroding Goals	12	Rule Beating	7
Seeking the Wrong Goal	11	Limits to Growth	4
Success to the Successful	8	Seeking the Wrong Goal	3
Table 4-1 (cont'd)			
Rule Beating	8	Fixes That Fail	1
Squeaky Wheel Gets the Grease	2	Success to the Successful	1
Accidental Foes	1	Squeaky Wheel Gets the Grease	1
Escalation	1		

Table 4-2 Actors and Stocks by Frequency

Actors and Stocks by Frequency			
Top 10 Stocks	**Frequency**	**Top 10 Actors**	**Frequency**
Capacity to Act	15	Food Pantries	33
Food Quality	15	Consumers	26
Knowledge of Food	12	Vulnerable People	22
Funding	9	Grocery Stores	13
Capacity to Collaborate	9	Flint Residents	13
Time	7	Non-Profit Organizations	10
Capacity to Provide Services	7	Farms/Nonprofit	10
Social Capital	6	Farmers Market	5
Food Prices	6	Gardeners	5
Food Waste	6	Corner stores	4
Total	**92**	**Total**	**141**

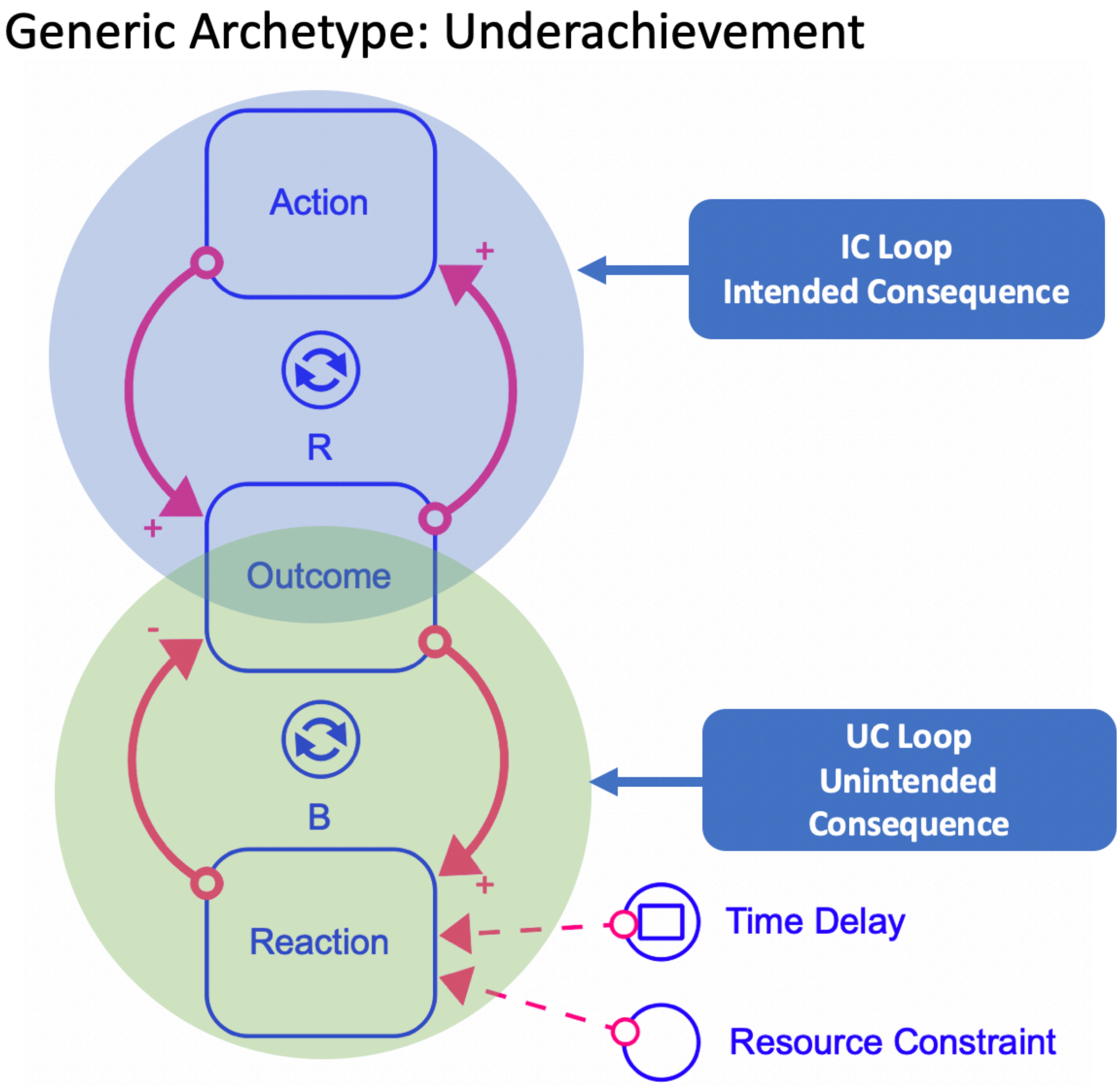
Examples

Though it is beyond the scope of this paper to present the context-specific findings and uncovered themes, below, we provide examples of each generic archetype. We demonstrate how the purposive text was translated into important stocks, actors, actions, intended consequences (*ic*) and unintended consequences (*uc*), and how they were used to determine the appropriate generic archetype structure. The context for the exercise was focused on various stakeholders in a Midwest community and their perspectives on the past, present, and future of their food system.

Underachievement

Wolstenholme describes the Underachievement archetype as having a composition of a reinforcing *ic* loop and a balancing *uc* loop with delay. In these instances, the *ic* is trying to achieve a successful outcome from the action but is dampened by the result of a resource constraint, or a balancing *uc* loop. In our analysis, this was the most prevalent identified archetype. For semi-generic archetypes, we identified limits to growth, limits to success, growth and underinvestment, and fixes that fail (see Discussion).

Figure 4-2 Generic Archetypes Underachievement



An example of Underachievement can be found in the following quote of a participant describing the growth of the local food system being restricted by its own rising complexity:

> "Our state has a lot of associations and networks and groups like that, since our community is a key community in the state, they are part of these networks of information and resources, food bank networks, community action network, statewide organizations, really provided help and best practices... more now. They are everywhere and it begins to get to the point we can't even act as one"

Another related example that we found repeatedly is illustrated in the following quote with a participant describing the increased complexity of the food system makes continued coordination and possibly management and success more difficult to define or achieve:

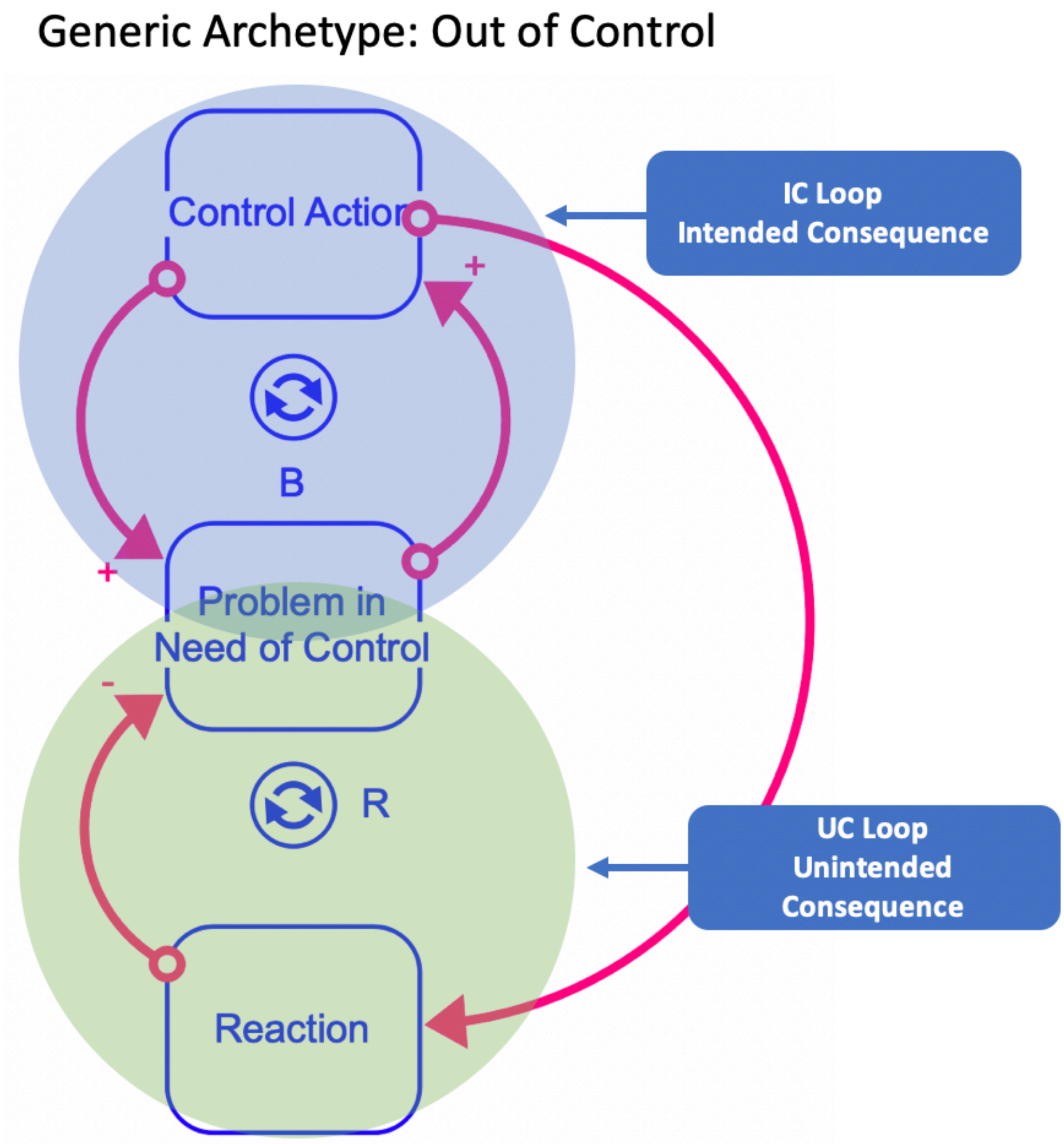
> "… when I first started here, it was simpler, there is an oversaturation of things that are happening that makes coordination difficult for us in organizations and difficult for consumers, there feels like there is a lot going on, I don't want to say too much, but you know we probably lose sight of where we are going".

In these examples, it is evident that the dynamics are playing out on different scales, and it is necessary to think carefully about system boundaries. At the most individualized level, we can see that the major actors are individual organizations or consumers. The major stock is the count of different organizations in the system. The dynamics at play are that the food system is growing, offering more services and choices, creating the *ic* loop. The *uc* loop plays out on the individual level, where actors find it more difficult to navigate these resources or collaborate with other organizations in which connections could be made. As it becomes more challenging to navigate or collaborate in this system, it happens less so, limiting the system's growth. If this happened without delay, the system would likely tend towards an equilibrium size or complexity, but because delays are likely present, oscillatory patterns are likely.

Out-of-control

Wolstenholme describes the Out-of-control archetype as having a composition of a balancing *ic* loop and a reinforcing *uc* loop with delay. In these instances, the *ic* is trying to control the extent of a problem through an action. However, this creates a reaction (possibly from another sector), resulting in a worsening of the problem causing the problem symptom to become more and more out of control.

Figure 4-3 Generic Archetype: Out of Control



In our analysis, this was the second most prevalently identified archetype. For semi-generic archetypes, we identified fixes that fail, shifting the burden and accidental adversaries.

An example of Out-of-Control can be found in the following quotes of two participants describing the problem of food insecurity with respect to free food distributions:

First Person: "Another thing i hear a lot from, two agencies in particular, but this is more of a general thing that doesn't work well, but there is there is a fact that there is so much free food distribution means that people are less likely to support urban agriculture with dollars. If people expect it to be, maybe not expect, but if you have a free source of produce you are less likely to purchase it and these urban agriculture folks need to eat too"

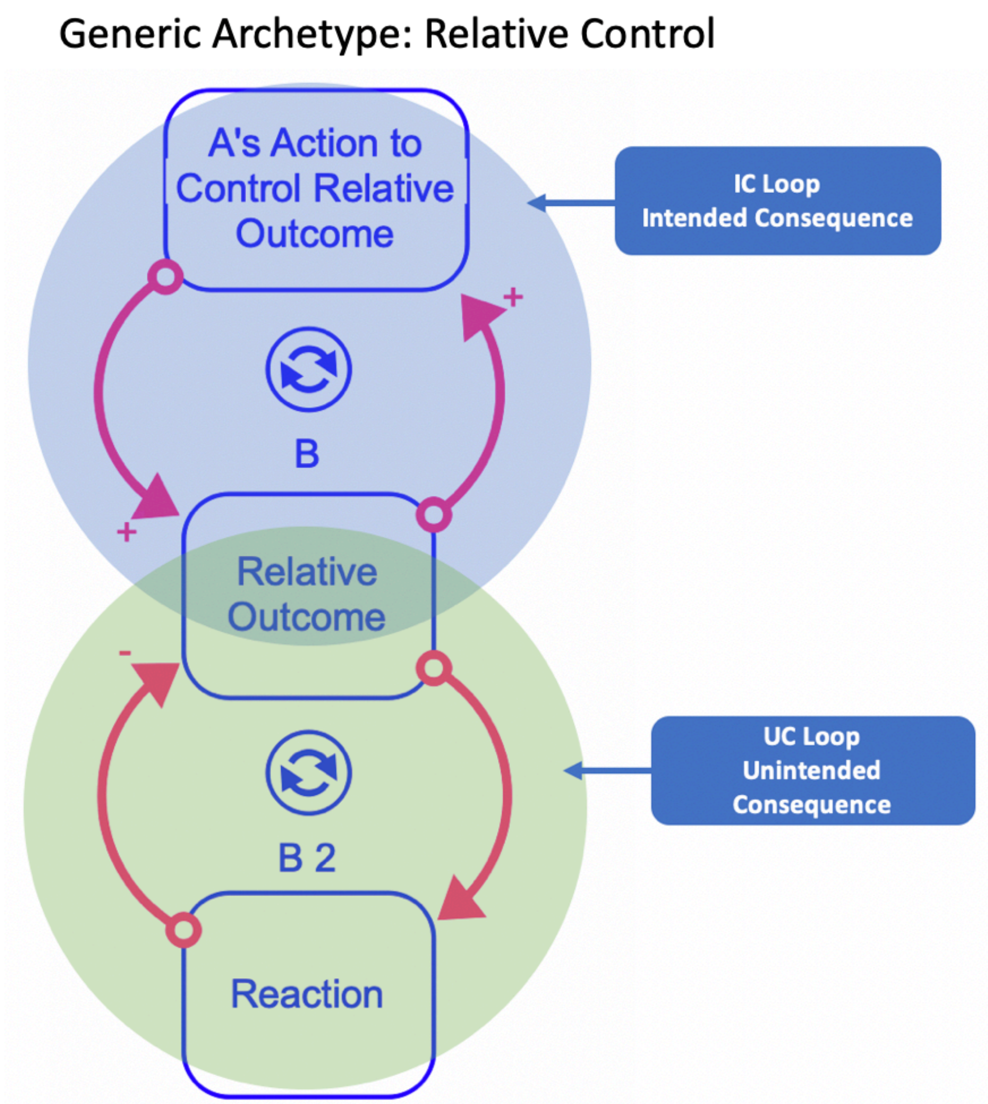
Second Person: "We have seen that with the numbers and the people applying for food assistance, declining and changing, because of the reaction to the increase of free food. And then there is the concern what if that goes away, or if it goes way, then what? so finding different avenues to getting people signed up for these assistance programs even though it may look like they don't need it right now".

The main stock in the above example is Food Security, with actors being food pantries and urban agriculture entrepreneurs. The action is food distributions at food pantries, which creates the *ic* loop, balancing the level of food insecurity. The *uc* loop is played out in increased dependency, and the decrease of willingness to pay for urban agriculture products as the distributions crowd out the market.

Relative Control

Wolstenholme describes the Relative Control archetype as having a composition of two balancing feedback loops, both the *ic* and the *uc* loops. The *ic* consists of a loop with an action intended to control a relative outcome. However, this action signals to another sector or part of the system to compromise the outcome of the action. In this archetype delays can be present on both loops or only one. In our analysis this was the third most prevalently identified archetype. For semi-generic archetypes, we identified eroding goals and escalation.

Figure 4-4 Generic Archetype: Relative Control



An example of Relative Control can be found in the following quote with a participant discussing the quality of food found at grocery stores in his community:

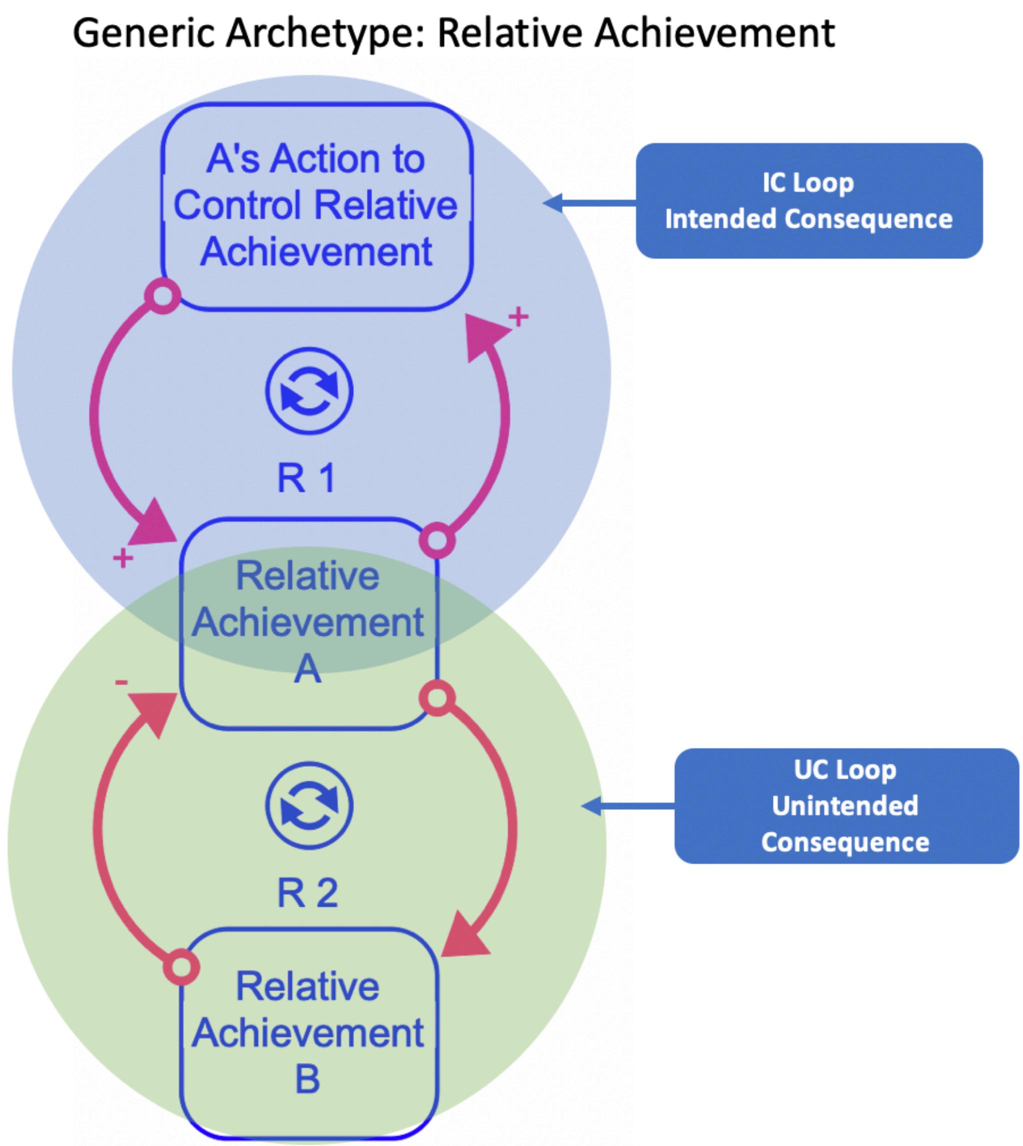
> "I would say that when Save-A-Lot came, the quality went down all around the board. Like, I feel like because Save-a-lot was here, and they had this low-quality product, and the people bought it, so the rest of the stores started doing it too. Everything started lowering quality. Then you had all of this "great value" here, and "great value" there. Next thing you know, and it is lower and lower quality and a steeper price, and it is actually not good."

The main stock of interest is Food Quality, with actors being Grocery Stores and Budget Grocers. As is described, the action or *ic* loop is created by Save-a-Lot, a budget grocer, who enters the market with what the participant describes as lower quality food. This creates a *uc* loop in the rest of the Grocery Stores, which lowers their quality, presumably staying competitive on prices. The participant describes an overall decrease of quality over time and multiple sectors of the food system trying to achieve relative control of the market. This example also illustrates how the same two-loop structure can explain escalation and Drifting Goal dynamics. Escalation between the competing grocers and Drifting Goals with the slow shift of acceptable quality foods in the community. This dynamic happens when the acceptable quality is compared to recent memory, allowing quality to decrease, with a lowering of standards incrementally.

Relative Achievement

Wolstenholme describes the Relative Achievement as having a composition of two reinforcing feedback loops, both the *ic* and *uc* loops. The *ic* consists of a loop with an action intended to achieve a relative advantage from an action. However, this action and resulting achievement is at the expense of other sectors or parts of the system. Here the *ic* loop magnifies the relative outcome in a zero-sum game. In our analysis, this was the Fourth most prevalently identified archetype. For semi-generic archetypes, we identified success to the successful.

Figure 4-5 Generic Archetype: Relative Achievement



An example of how Relative Achievement was identified in our data is found in the quote below with a participant describing the dynamics of the farmers market in their community. They describe how prepared food vendors attract more attention, have higher-priced products, and can pay for multiple spots. They discuss how this has changed the farmers market to be more of a prepared food vending area than a market geared towards the direct sale of produce.

> "Spots at farmers market used to be cheap, food trucks driving up booth price, driving farmers away. Less about people buying fresh produce….Right now its more people making better, when it was outside it was better, now it is much more commercialized. You now have more restaurants... it went commercial and got more expensive…right now you have BBQ trucks that are taking up three spots that a farmer can't afford to pay. You go down there right now, they have a perfect spot, that takes up three spots with a BBQ truck., selling they BBQ which sell for a high price. And it have nothing to do with no fruits or vegetables, but they have the money to pay it. I have a buddy right now that his and his wife got a spot in there and they started paying about $70 dollars, and right now they are up to around 300 dollars. …and now it ain't about the food, it is about the money, it ain't about the vegetables, it's not about the market. You can take the title of Farmers market, you can take that title off and that place will still survive… "

The main stocks in this example are the relative market share of vendors at the farmers market and farmer's access to the market. The actors are Prepared Food Vendors and Fruit and Vegetable Vendors. The *ic* loop is reinforcing the Prepared Food Vendors' action using their higher profit margins and sales to purchase more spaces in the farmers market at the detriment to the Fruit and Vegetable Vendors, which is captured in the *uc* loop.

Discussion

We coded each instance for both the generic and semi-generic archetypes. Comparing the two types of archetypes for their usefulness can inform modeling practice and systems thinking education. Though it largely depends on what the archetype analysis will be used for and who will be engaged in the process. We found that the generic archetypes were exact and precise in articulating system structure, causing certain problem behaviors. With this precision, however, came a necessity for higher resolution data that examined the causal structure of the observation. In the majority of instances, the participants described these causal structures with enough detail that we were able to identify the generic archetype. This precision provided by the generic archetypes also led to unexpected findings related to the semi-generic archetypes. For instance, Fixes That Fail, the semi-generic archetype, was identified in many instances that were either Underachievement, Out of Control, or Relative Achievement. The story-like features of semi-generic archetypes may focus on the narrative and place less emphasis on the structure, something valued by systems thinking. Examining our case of Fixes That Fail, it was often in instances where someone described a situation in which a solution or policy action is taken and but it does not create the intended results. Though this meets the criteria of the codebook for Fixes That Fail, it overlooks what kind of problem they are describing and what sort of feedback loop is dominant over it. It also does not consider why the action failed: due to a limit of another resource or stock (similar to a Limits to Growth), or because of unintended consequences, or path dependent behavior. This example illustrates the benefits of the generic archetypes and the codebook approach.

However, the generic archetypes require a more advanced understanding of feedback loops, the behavior they cause, how they interact, and how feedback dominance operates.

Largely, the text data provided examples of generic archetypes with rich enough descriptions to identify generic archetypes and provide a starting point for model conceptualization. Our success in this process could be due to the structure of the visioning protocol to think about the past, present, and future. This is consistent with other system dynamics literature around using visioning and envisioning processes as an effective technique in modeling (Van den Belt, 2004). Considering the instances where the data was insufficient to identify a generic archetype, it is not to say that it is not useful in the modeling process. Broadly, these were instances of reference modes or behavior overtime that lacked a causal explanation for what was happening. These can be referenced again during the modeling process as touchstones for places to seek more information.

However, it should be noted that best practices in facilitation could make this data more useful to the modeling process. Namely, facilitating a process that seeks causal explanations for described behavior with a caveat that "I don't know" is acceptable. In our examples, it was unclear if there was an implied causal explanation, or if the participant knew why something happened, if they were unsure, or lacked any knowledge within their role to answer because they were not asked.

More empirical analysis is required on the use of archetypes in systems thinking practice. Though our findings suggest that the generic archetypes allow for participants to identify causal structures and feedback loops governing their system, the practice of doing so takes sophisticated systems thinking skills. We would hypothesize that semi-generic archetypes are useful in getting new system thinkers to identify when dealing with a complex system and can serve as a warning or draw attention to a system's complexity. It would be interesting to determine, through the use of systems thinking learning scale, or systems thinking self-efficacy scale, which approach works best for the different intended outcomes.

Another area where these findings could be useful is developing an archetype script (scriptopedia) for Group Model Building processes. Here, instead of purposive text data, we would want a group of people who are expert knowledge holders to engage in the process of conceptualizing and identifying the archetypes themselves. Here we believe the codebook we presented could be used as a guiding framework for this script.

Conclusion

In this paper, we demonstrated two things. 1. That system archetypes can be useful in multiple stages of modeling and help retain a link to the original data as abstraction and simplification processes dominant the modeling translation. 2. We demonstrated the utility of using archetypes in a coding schema for analyzing qualitative modeling. This study demonstrates that a systematic approach to identifying generic archetypes can be used for analyzing data and provide consistency throughout the process. Being explicit about the structures the modelers are seeing provides a way to be in constant communication with data, addressing the old adage that modeling is more of an art than a science. Furthermore, these links to the data can aid in client or community-centered modeling by creating a boundary object to connect the physical structure of the model to the data that generated its structure.

While the coding process illustrated in this study was precise in thinking about generic causal structures in the data and provided insights over the use of semi-generic archetypes, it was not without its challenges. Like any qualitative analysis, it was labor-intensive and took many iterations of analysis to determine the archetypes and relevant units of analysis. Developing future work to understand system boundaries, especially given their importance in masking the unintended consequences, is needed. Though this is not unique to the purposive text as boundary work in many aspects of system dynamics has been overlooked, and further research could yield important findings. The coding process also needs to be replicated to collectively test its usefulness in identifying and mapping structures operating in systems. Findings from these efforts could inform not only the formal modeling process but build on the pedagogy of systems thinking, and client and community-centered practice.

Chapter 5 Conclusions

Introduction

This dissertation included three studies that examined interdependence in community issues and contributes to the literature on applying participatory modeling to place-based problems. The unifying theme of interdependence created a space to think critically about the structures that drive systems in communities. This dissertation contributes to the field of sustainability science, defined as place-based problem-oriented inquiry that focuses on applying knowledge to action (Miller, 2013). This dissertation shows how sustainability science can interface with complex system features of interdependence, path dependent time effects (Meadows, 2002), with participatory research which requires an appreciation for community held, experiential knowledge (Greenwood & Levin, 2006; Whyte, Greenwood, & Lazes, 1991). The primary goal of community-based sustainability research is to understand endemic sustainability problems *with* community partners (Deakin & Reid, 2014). It is to integrate a diversity of information in a knowledge creation process based on reciprocal learning (Wittmayer & Schäpke, 2014). As this dissertation demonstrates, combining a participatory method with complex systems research requires an interdisciplinary methodology, that interfaces with network science, informatics, participatory inquiry and mathematical modeling.

This dissertation makes methodological contributions in the integration of different types of data to understand community problems. The studies in Chapters 3 and 4 were largely completed during the 2020 Covid 19 pandemic. The resulting restrictions to research and data collection required adapting and using different kinds of data in combination to understand the research questions. Though this research context was unique, it reflects the changing environment in which community-based research is often conducted, including accelerated timelines which rarely accommodate lengthy data collection and analysis processes (Chambers, 1994). By integrating community knowledge with commonly used modeling modes, we avoided an extensive data collection and model formulation process which may have prevented the use of systems methods to address these community problems.

As shown in Chapter 3, data collected primarily to understand important stakeholders in the inclusion in the broader project design, was used in a new way and treated as a representation of the network structure in a community. This study used the resulting structures as a object to understand aspects of the food security system's connectivity and resilience. For the first time in community-based research, the small-world-quotient was used to examine the structural capacity for simultaneous global and local efficiency. This demonstrates the utility and necessity of relooking at data in different ways and from a plurality of methods.

This dissertation also furthers our understanding of how to research these types of problems in ways that are explicit, open to communicative opportunities, and links any and all modeling efforts to the data of lived experience. In Chapter 4, a process for explicit translation of community narratives into generic feedback structures was demonstrated. This study utilized secondary data that was originally collected as part of a food system visioning workshop. This shows how different kinds of data, can inform modelers and researchers of the underlying structures driving systems. This chapter also illustrated how necessary it is to be transparent about claims made with community held data, and how slight discrepancies in meaning can lead to vastly different interpretations of the causal structure behind a particular system level outcome. It provides a case study on the importance of being explicit about structure in understanding the causal mechanisms behind what participants are experiencing.

In Chapter 2, the field of participatory modeling is mapped to show its characteristics and subfields that approach participation and modeling differently. By understanding the connections and communities of scholars in this work, the emergence of separate but related research fronts was revealed. These research fronts, examined as networks, explains how practitioners approach both participation and modeling. At the broadest levels, there are practitioners in the field that use PM as a tool to enhance participatory processes. This subfield addresses the challenges of shared understanding and conflict with different modeling tools. This is contrasted with the how others in the field of PM use participation and collective intelligence as an asset in creating better, more complete, models of contested systems. This partition of the field is defined in the approach and purpose of PM. Though there can be some significant overlap in how modelers approach their work, these fundamental goals should be clear to participants and those evaluating the modeling effort.

These chapters together point to future research directions in the area of applied systems science and participatory modeling. What remains uncertain across these studies is how participants (or community members) respond to the modeling process and its intermediate and end products. An evaluation of how PM accomplishes goals for participants is necessary. One area of limited understanding across all threads of PM that should be expanded on is the area of systems thinking self-efficacy. As shown in this dissertation, there are many modes of model building with participants. Often a modeler engages with community partners to tackle a complex of wicked problem. It is unclear, however, how participants in these various settings engage with the modeling tools and if it increases their perceived ability to act as problem owners.

In the case study in Chapter 3 on stakeholder mapping, it remains unclear how participants would engage with and understand the network maps. This leads to open questions for stakeholder mapping and diagraming: Are these diagrams useful for individual actors and how the collaborate? Are structural holes evident to participants? How much training is necessary for participants to glean actionable information from these diagrams?

Chapter 4 took a different approach to describing system dynamics as archetypes and narratives. It remains unclear how accessible the fully generic archetypes are for community members, and if this approach enhances their understanding or is confusing. Future research focused on assessing the utility of this approach for participants is necessary, but this preliminary work demonstrates the near universality of structure in complex community problems.

APPENDICES

APPENDIX A Stakeholder Mapping Protocol

2019 0206 Flint LP stakeholder mapping protocol
Who are the important people/groups in Flint, Beecher and Burton Food System (including those based outside but that affect the food system)?

Yellow post-it notes

Note: May have to clump people/organizations to be feasible given the scale i.e. food pantries, churches.
Note: Identify whether if outside Flint on post-it with (E)
How are these groups linked to each other?
Flow of finance ($) = red
Flow of information = blue
What direction is the relationship?

APPENDIX B Archetype Codebook

Fully Generic System Archetype Codebook	
Code	**Description**
Major Stocks	A stock is a variable of interest that can increase or decrease. These are usually discussed as important quantities or qualities of the system.
Major Actors	Actors can be types of individuals, organizations, or agencies that are involved in the system (explicitly or implicitly)
Problem	referred to something in the system that is either not working, underperforming, working well, or in need of elimination.
Action	Something that actors in the system have tried as a way to remedy the problem
Intended Consequences	Intended outcome of an action. Expressed as a feedback loop
Unintended Consequences	The unexpected outcome of the action, often happening with delay or outside of the sectoral boundaries of the major actors conducting the action.
Delay	Delays could either be explicitly referenced in the text or inferred by the coder from the described system behavior
Food System Outcome	This describes what primary food system outcome the extracted data is referring to: Access, Availability, Utilization, Social Welfare Environmental Capital

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