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Master Thesis

A Formal Theory of Resilience

by

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Abstract

Over the past decade, the concept of resilience has gained momentum in climate change and disaster research. Although the relevance of resilience in dealing with environmental changes has been acknowledged by these communities, an impasse in research occurs when trying to extract the crux of resilience and transform it into an implementable entity in vulnerability assessments and information systems. This debacle is attributed to the multiplicity of definitions across Ecology, Climate Change, Disaster Management and Sustainability Science, which obscures the meaning of the concept and prevents its operationalization. In order to forge ahead with concerted efforts to manage climate induced changes unto societies, the ambiguities contained within resilience must be addressed. To tackle the miscommunication that follows the concept, this dissertation posits a formal theory of resilience. Drawing on the idea of semantic reference systems, ontology engineering principles are utilized to construct the formal theory. In this sense, a resilience ontology provides a semantic reference frame for the concept. Through the ontology, key terms, which fall under the purview of resilience are defined. Moreover, the relationships between terms are formally made explicit and the linkage between resilience and the process of adaptation is made clear. Overall, the ontology constrains the interpretation of resilience thereby quelling the ambiguities that permeate the concept. This formal theory of resilience marks the initial steps towards its operationalization.

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List of Abbreviations

Term	**Abbreviations**
Description Logic	DL
Descriptive Ontology for Linguistic and Cognitive Engineering	DOLCE
Landscape-based Environmental System Analysis and Modeling lab	LESAM
Intergovernmental Panel on Climate Change	IPCC
Resilience Alliance	RA
Socio-ecological system	SES
Web Ontology Language	OWL
United Nations International Strategy for Disaster Reduction	UN/ISDR

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Chapter 1

Introduction

After thirty years of academic analysis and debate the definition of resilience has become so broad as to render it almost meaningless (Klein et al., 2003).

Over the past decade, the concept of resilience has gained momentum in climate change and disaster research. Stemming from Ecology, resilience is defined as "a measure of the ability of these systems to absorb changes of state variable, driving variables and parameters and still persist" (Holling, 1973, p. 17). As the pertinence of the concept was unmasked throughout the years, various research communities have acknowledged the role of resilience in dealing with environmental change. In so doing, these communities have departed from the original conceptualization and adapted the concept to fit their own research purposes resulting in various interpretations of the concept. Consequently, "after years of academic analysis and debate the definition of resilience has become so broad as to render it almost meaningless" (Klein et al., 2003).

An impasse in climate related research occurs in trying to extract the crux of resilience and translate it into an implementable entity in vulnerability and resilience assessments as well as information systems. This is attributed to the multiplicity of resilience definitions, which creates a bottleneck along the path to operationalization (Klein et al., 2003). According to

Miller et al. (2010), both vulnerability and resilience communities have fallen short in reaching the requirements of sustainability in face of environmental variability. Part of the reason is imputed to the conceptual fuzziness imbued within the concepts, which is further compounded by the lack of integration between both research communities (Miller et al., 2010).

Whilst the vulnerability community has taken the steps towards operationalization of its concept (see (Ionescu et al., 2009)), the resilience community has not caught on. Klein et al. (2003) highlighted the need for resilience research to develop an operational definition. Operationalization entails the physical and mental measurement of a concept relative to a reference framework (Bridgeman, 1927). For example, the concept of weight only becomes operational when the kilogram reference frame is applied. Therefore, making resilience operational goes beyond expressing a definition as suggested by Klein et al. (2003) and extends to the entities that constitute resilience and their relations. To address the ambiguousness of resilience, these entities must be ordered and their relations formally specified. In this regard, an ontology can play a vital role to elucidate the concept of resilience. Akin to geographic reference systems, which provide a formal structure wherein positions over the earth's surface can be measured to a datum and projected in a coordinate system, an ontology provides a formal structure where concepts can be semantically measured and aligned to a formal vocabulary within a constrained system (Kuhn, 2003). Being cognizant of the bottleneck that occurs on the conceptual level, this scientific work therefore hinges on the idea of operationalization (Klein et al., 2003) by developing a semantic reference frame for resilience through ontologies.

1.1 Resilience and Climate Change

Climate variability and its impact on societies have gained currency in research over the years. As the earth's temperature intensifies due to anthropogenic induced green house gas concentration, regional climates would vary as the earth tries to achieve a new state of equilibrium. This volatile position, which the earth has entered would unmask socio-ecological systems to sea level rise, climatic variations, hydrological changes, food insecurities, diseases as well as displacement of biodiversity, however, these changes would not occur uniformly across the earth. For example, increased warming has been attributed to longer crop growing periods in Eurasia while a reduction has been recorded for Sahelian countries (Rosenzweig et al., 2007). If not managed, the non-uniformity in changes could further shift global economic paradigms as development milestones are undermined, which can have deleterious multiplier effects especially for developing countries. This was evident for the island of Grenada in the aftermath of Hurricane Ivan in 2004. For Grenada, the total cost of damages was estimated to be twice that of the Gross Domestic Product (GDP) and future economic growth postulated at -1.4% per year compared to the 5.4% per annum calculated prior to the natural disaster (Mimura et al., 2007). In the midst of climate variability, Mimura et al. (2007) stated that the "challenge [of societies] therefore is to shape and manage development that also builds resilience to shocks."

The environment and by extension society has in its framework the ability to cope with these changes, an ability deemed as resilience. According to Burkett et al. (2001), enhancing resilience is synonymous with reducing society's risk to climate change. In this sense, resilience is responsible for reducing society's vulnerability to these changes. Concomitantly, Manyena (2006) stated that the concept of resilience aids in providing a holistic assimilation of risk and vulnerability. As the author puts it, resilience "fills a void by addressing the soft perspective of vulnerability and allows us to rethink the prevalent $risk = hazard \times vulnerability$ equation" (Manyena, 2006). Mimura (1999) and Klein and Nicholls (1999) both acknowledged the salience of resilience as a determinant for vulnerability with Klein and Nicholls (1999) going further to suggest that a system's resilience be synthesized with the Intergovernmental Panel on Climate Change (IPCC) Common Methodology for vulnerability assessments (Figure 1.1). However, this suggestion is not considered in the latest approaches in vulnerability assessment (see Carter et al. (2007)) and instead the term resilience is loosely used without a clear definition. Here, adaptation is seen as the panacea to reduce vulnerability and enhance resilience of a system. Though the salience of resilience is recognized, the pathways to determine resilience or what being resilient entails in dealing with vulnerabilities was not expounded in the IPCC report.

Resilience and vulnerability are concepts that are complementary in nature linked through socio-ecological system dynamics in face of disturbances. Miller et al. (2010) strongly advocated that vulnerability and resilience approaches in concert can provide new avenues to tackle uncertainty and environmental change fuelled by global warming. The authors highlighted points of convergence in theory, methodology and policy formation wherein resilience and vulnerability can lend support to each other since both concepts evaluate aspects of socio-ecological systems. In a similar light, Walker et al. (2002) highlighted the important role socio-ecological systems could play in face of climate change. The authors proposed that emphasis should be placed on understanding socio-ecological system behaviour and its resilience to disturbances, a term the authors coined as 'resilience analysis and management.' Resilience researchers believe that dealing with climate induced changes through a resilience lens can provide new avenues in dealing with variability in the context of sustainability.

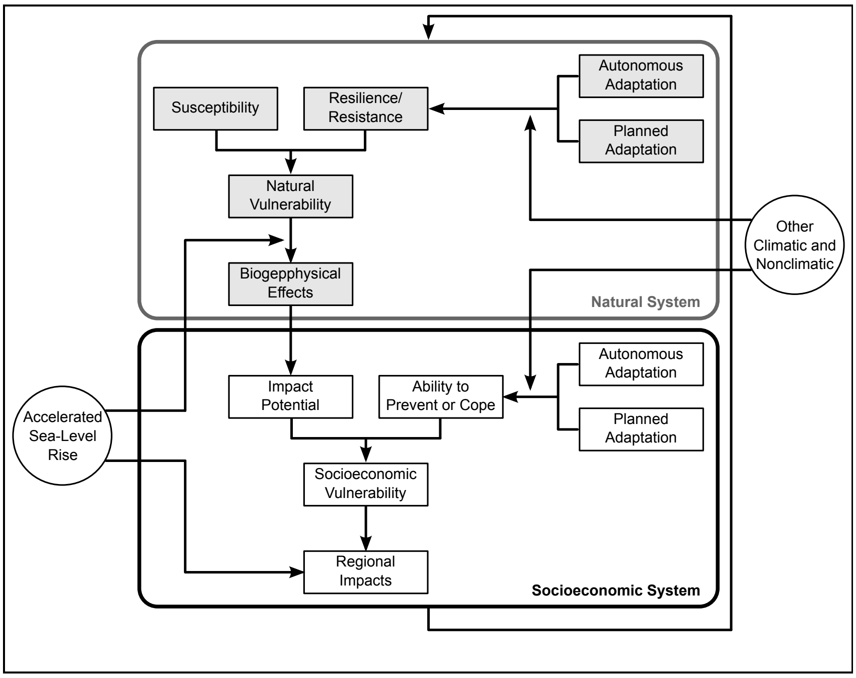

Figure 1.1: Conceptual Framework for Coastal Vulnerability Assessments with Resilience Integrated (Klein and Nicholls, 1999).

1.2 Research Question

Based on the definitional issues, which cloud the meaning of resilience as well as hinders its operationalization in research, the following questions were formulated:

1. How can a formal theory address the conceptual issues that underpin resilience?

2. What are the key concepts that constitute resilience and their relations to each other?

1.3 Aim and Objectives

This research aims to provide a formal theory of resilience to serve as a reference frame for the concept. Drawing on the idea of semantic reference systems by Kuhn (2003) and Kuhn and Raubal (2003), a semantic reference frame for resilience can:

- Formally ascertain a vocabulary for resilience by explicitly stating the key entities and relations that underpin the concept. By structuring the real world view of resilience, the researcher can implement rules and perform reasoning tasks on data within a computational environment.

- Straightens out the conceptual inconsistencies that occur in resilience research. This makes recognizing linkages between concepts possible, for example between resilience and vulnerability.

- Formalizes the concept of resilience, which is a precursor for computational analysis of resilience.

- Offers a building block towards knowledge driven application development for example, in a geographic information system. In this regard, ontologies can be used to implement domain knowledge in programs (Guarino, 1998).

In order to achieve the overall aim outlined above, the following objectives were identified:

1. To disambiguate the concept of resilience.

2. To explicitly define the relationships between entities that constitute resilience.

3. To provide a formalization for the notion of resilience.

1.4 Scope

This scientific work presents a formal theory of resilience. Here, a formal theory refers to "a logical theory, which gives an explicit partial account" of the real world view of resilience (Guarino and Giaretta, 1995). Through the framework, the notion of socio-ecological resilience is addressed. Key entities, which are required for resilience to be perceived are described using the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE)[1] categories and basic primitive relations. However, the complex processes within these entities are not examined nor formally made explicit within the formal theory. In addition, the theory does not account for the temporal nature of these entities. Although the formal theory of resilience is intended for climate change and disaster management domains, it is also applicable to other fields that are concerned with socio-ecological system resilience, for example Ecology and Risk studies.

Assumptions

The following assumptions were made during the construction of the formal theory:

- **Resilience is a concept that can be measured**. This assumption stems from the idea of resilience operationalization put forward by Klein et al. (2003).

[1]DOLCE is a foundational ontology that is used to describe how things in the world should be modelled based on existing knowledge (Masolo et al., 2003).

- **A system adopts one strategy at a time when building resilience**. Support for this assumption is founded in resilience literature (see Chapter 3). For example, Adger (2000) highlighted that in face of food insecurity, a sample population in Africa and India under investigation chose to preserve their future income and consumption (adaptation) rather than maintaining their current state. This idea of a system choosing one strategy at a point in time is also conveyed in Handmer and Dovers' (1996) typology of resilience.

1.5 Related Work

There has been a plethora of work in resilience and towards its operationalization in disaster management, however the author did not unearth research pertaining to the formalization of resilience in climate change. Nonetheless, there has been ontology research done on resilience in computer science (see LAAS-CNRS (2008)) but unfortunately this falls outside the scope and purpose of the dissertation. Extensive resilience studies in the field of disaster management and climate variability is undertaken by the Landscape-based Environmental System Analysis and Modeling lab (LESAM) of the University of Buffalo[2]. This research group is involved in the development of a resilience toolkit that enables the user to quantify community resilience based on an index. The toolkit provides a platform for datasets to be integrated and analysed for coastal hazards. In a sense, resilience is made operational with the concept being measured against a ratio scale from 0 to 1. In a similar effort, the World Bank created the Open Data for Resilience Initiative, which enables the exchange of data across their platform to promote resilient decision-making by policy makers in face of natural disasters[3]. The purpose of the platform is to facilitate communication amongst decision makers as experts can upload or download community data that is pertinent to assessing risk and building resilient societies. At present, the World Bank has launched research into creating a

[2] http://lesami.geog.buffalo.edu/lesam/index_files/noaa_com_res.html. Accessed on December 12 2011

[3] http://www.gfdrr.org/gfdrr/opendri. Accessed on December 12 2011

resilience index.

What is common to both projects outlined above is the dearth of available information pertaining to the building blocks towards these applications. It is unclear whether or not a formal theory was created to underpin the applications and conceptual inconsistencies clarified prior to development. On the other hand, vulnerability research has already tackled its conceptual issues and a formalization of the concept was undertaken for the climate change community (see (Ionescu et al., 2009)). Ionescu et al. (2009) recognized the need for a formal theory to quell misinterpretations of the concept as well as to facilitate computational assessments. Although an ontology-based approach to their theory was not executed, the salience of a formalization was made clear. To the author's knowledge no formal theory of resilience applicable to climate change and disaster management exists. This scientific work therefore makes the first step in this direction.

1.6 Proposed Methodology

The formal theory of resilience rests on the pilars of knowledge representation principles. Here, an ontology as a form of knowledge representation is used to transmute the notion of resilience into a logical theory. By developing an ontology, the real world view of resilience can be organized with the relationships amongst its entities formally established and their meanings elucidated. The ontology is constructed using METHONTOLOGY (Gómez-Pérez et al., 2004), which is one of the core ontology engineering methodologies. Firstly, the notions of resilience across disciplines are examined and decomposed into a general resilience definition that is applicable across domains. Relations are ascribed to the entities within resilience according to the DOLCE upper-ontology categories and basic primitive relations. By aligning the resilience ontology to DOLCE, the ontology transcends into a semantic reference frame for resilience. In addition to concept relations, axioms are specified to constrain the interpretation of resilience in the ontology. The concept of resilience was then formalized in Description Logic

(DL)[4] and implemented in OWL-DL[5] using Protégé.

Keywords and Definitions

Formal theory. A logical representation of statements pertaining to a phenomenon comprising of axioms and inference rules (Woodcock and Loomes, 1988).

Ontology (Computer Science). A hierarchy of concepts related by subsumption relationships [and] in more sophisticated cases suitable axioms are added in order to express other relationships between concepts and to constrain their intended interpretation (Guarino, 1998).

Operationalization. The physical and mental measurement of a concept relative to a reference frame (Bridgeman, 1927).

Resilience. The ability of a system to cope with an external factor that undermines it, with the system bouncing back.

1.7 Conclusion

This chapter presented an overview of the scientific work, which is carried out in the dissertation. The importance of resilience in dealing with environmental change and the shortcoming of the concept in research were introduced to the reader. The conceptual issues, which limits the potential of the concept can be summarized in one term i.e. semantics. The semantics of resilience is not clear and hinders its operationalization as well as its integration with vulnerability. Consequently, this research posits to develop a formal theory of resilience to straighten out the conceptual fuzziness attached to the term while at the same time paving the road

[4] Description Logics (DL) is a formal language that is used to describe knowledge base and enable reasoning about this base (Nardi and Brachman, 2003).

[5] OWL-DL is a description logic specialization of the web ontology language (OWL). For more information see: `http://www.w3.org/TR/2004/REC-owl-guide-20040210/#OwlVarieties`. Accessed on December 12 2011)

towards its operationalization. The subsequent chapters therefore lay out the building blocks towards this goal:

- Chapter 2: This chapter presents a review of the formal theory approach used to create the resilience ontology.

- Chapter 3: Chapter 3 describes the knowledge acquisition phase of the ontology design process. A review of resilience literatures together with the disambiguation of the concepts are presented.

- Chapter 4: In Chapter 4, the conceptualization activity is executed. Here, the knowledge gained in the previous chapter is transmuted into a semi-formal state. Furthermore, the alignment of the model to DOLCE and the introduction of the content ontology design pattern to overcome modelling resilience in DOLCE is discussed.

- Chapter 5: In this chapter, the results of the thesis is laid out. Here, the formal theory of resilience encoded in Description Logic together with its implementation in Protégé is detailed to the reader.

- Chapter 6: Chapter 6 presents the evaluation of the formal theory of resilience. First, a technical assessment of the ontology is carried out. Subsequently, a comparison of the theory with established conceptualizations in undertaken to assess the level of agreement.

- Chapter 7: Chapter 7 concludes the dissertation by re-stating the achievements of the research and future direction.

Chapter 2

Formal Theory Approach

Ontological Engineering is a craft rather than a science (Gomez et al 1996).

2.1 Introduction

A resilience ontology can be seen as a befitting starting point to aid with the conceptual blockage, which hinders research. The use of an ontology can play a salient role here, since it is concerned with the a priori nature of reality and its organization (Guarino, 1995). This chapter therefore puts forward the methodology undertaken to establish a formal theory for resilience. Firstly, a review of knowledge and ontologies as a form of knowledge representation is presented. Subsequently, the idea of operationalization as it pertains to ontologies is introduced. Finally, the ontology design process is outlined and the METHONTOLOGY approach applied in this research is explained.

2.2 Knowledge

> Wouldn't it be neat if we could write down everything people know in a formal language? Damn it, let's give it a shot! [...] If we want to be able to represent anything, then we get further and further from the practicalities of frame organization, and deeper and deeper into the quagmire of logic and philosophy (McDermott 1993 as reviewed in (Guarino, 1995)).

The above excerpt is a befitting starting point into the discussion of knowledge representation and ontology. Before one can delve into the logical and philosophical representation of *anything*, there must be clarification of what one desires to represent. Ideally, this *anything* would refer to the human conceptualization of the real world. In keeping with the direction of this research, *anything* here would relate to embodying, as best as possible, the categories of resilience that span across academia. Our conceptualizations of the world stem from the internalization of entities observed directly or indirectly, which researchers contribute to our knowledge experience (Plotkin, 1997). Nevertheless, providing a specific answer to the question 'What is knowledge?' is heavily debated in the field of epistemology.

According to Plotkin (1997), the discipline of epistemology deals with the validity of knowledge. This knowledge in its most general form could be considered as (Cortada and Woods, 2000, p. 13): i) "a state of knowing;" ii) "the capacity for action" and iii) "codified facts, methods and principles." The second element of knowledge is reminiscent of knowledge taken in the computer science context as put forward by Newell (1982), wherein knowledge has the facade of being functional. The first generalization of knowledge (state of knowing) has been heavily debated in philosophy. Plotkin (1997) also identified this abstract notion of which knowing could be of two types: knowledge known by mind or knowledge known through senses. As Plotkin (1997) puts it, knowledge by mind entails "events in the head that corresponds to the activation of memory processes and occur at the time of the knowledge claim" whereas knowledge through senses entails knowing via "immediate sensory experiences." For example, recalling Pythagoras' theorem would be one form of knowing by mind as it invokes tapping into memory to do so whereas describing the object in front of you at this moment would be a form of knowing via one's sensors.

Furthermore, Plotkin (1997) linked the former to the philosophical ideology of Rationalism and the latter to the ideology of Empiricism. In Rationalism, knowledge is gained a priori i.e. independent of sense experience and is attained through our own deduction and innate capabilities (Markie, 2004). On the other hand, empiricism denounces the claims made in the former and experience is considered as the only source of knowledge (Markie, 2004). However, Plotkin's (1997) idea of knowledge went beyond the general and philosophical abstractions and was taken in an evolutionary context. In this form, knowledge was deemed as "the relationship between the organization of any part of a living creature's body and particular aspects of order in the world outside of that creature" (Plotkin, 1997, p. 20). Other researchers of knowledge regarded this entity as "a fluid mix of framed experience, values, contextual information and expert insight that provides a framework for evaluating and incorporating new experiences and information [and] originates and is applied to the minds of knowers" (Davenport and Prusack as cited in Cortada and Woods (2000)). Regardless, of how human knowledge is obtained, one idiosyncrasy is that knowledge can be shared. The purpose here is not to choose or put forward claims in favour of a particular school of thought but to just touch on the philosophical foundation of knowledge in the scope of knowledge representation.

Orthogonal to the philosophical perspective of knowledge, the field of Computer Science is engrossed with the formalization and representation of knowledge rather than its nature. Here, knowledge has a functional utility and is regarded as "whatever can be ascribed to an agent such that its behaviour can be computed according to the principle of rationality" (Newell, 1982, p.9). Newell (1982) coined the term knowledge level in Artificial Intelligence wherein knowledge is taken with regards to tasks and goals to be achieved in a rational manner by the agent within an environment such that the environment influences the manner in which tasks are achieved. In his stratified view of computer systems, Newell's knowledge level is placed above the system's logic level through which knowledge is realized (Figure 2.1). This level is a mere abstraction that contains the goals, the requirements to achieve them and the know how to do so. Newell's idea of knowledge ushered the way in which knowledge is engineered in systems based on agent behaviour bringing into focus the modelling view of knowledge.

Conversely, Clancey (1989) reinterpreted the knowledge level in his discussion on modeling system interactions. According to the author, knowledge is subjected to "the observer's point of view in the process of making sense" (Clancey, 1989, p. 289) as well as it accounts for the expert's awareness of the agent's behaviour and environment. It is this view of knowledge held by Clancey that is applied within the formal theory of resilience. In an attempt to make sense of the various conceptualizations of resilience, the resilience knowledge represented is based on the author's interpretation of resilience with regards to socio-ecological systems put forward by experts' observations of systems' behaviour in face of climate induced environmental change.

In this section, both philosophical and Computer Science notions of knowledge were presented. It would be remiss to discuss in this chapter ontologies as a form of knowledge representation for resilience without reviewing the foundation of knowledge. The review of knowledge showed that computer science regards knowledge in a functional sense unlike its philosophical counterpart. Nonetheless, this functional view of knowledge that is subjected to the observer still bares its roots in philosophy as the observer adopts one of the tenets of knowledge to essentially attain it.

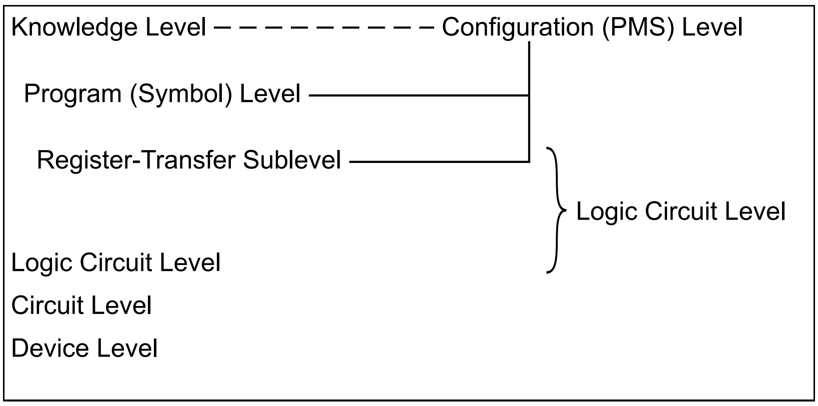

Figure 2.1: The Knowledge Level (Newell, 1982).

2.3 Ontology in Philosophy vs. ontology in Computer Science

The role of the knowledge representation community constitutes embodying knowledge in a form that is machine compatible so that information systems can become intelligent. This task has transcended across the Artificial Intelligence domain and into several other disciplines such as Geoinformatics, which is concerned with understanding the structure of the geographic world. The objective of this scientific work is to formalize resilience as a means of initiating the building blocks for its operationalization as well as a practical application for example in a Geographic Information System (GIS). Before the bigger picture could be achieved, there is work to be done on the knowledge base for resilience. A knowledge base houses the description of facts and claims about the domain of interest in logical form (Grimm et al., 2007). One method of constructing knowledge bases is through the use of ontologies. According to Guarino (1995), ontologies can play a vital role in the construction of high quality knowledge bases since it is concerned with the " a priori nature [and organization] of reality[...]by making distinctions among the entities of the world and the meta-level categories used to model the world."

In computer science, ontologies are viewed as computational artifacts (Grimm et al., 2007) that can encode knowledge in terms of their concepts and relations and expressed through the use of logic. However, a clear distinction is made by researchers between Ontology and ontology where the capitalized term refers to the philosophical discipline and the latter as a method in computer science (Guarino and Giaretta, 1995; Fonseca, 2007). In Philosophy, Ontology as a branch of metaphysics is concerned with the state of being, its essence and existence (Smith, 2003; Gómez-Pérez et al., 2004). According to Smith (2003), Metaphysics dates back to Aristotle, which Aristotle referred to as the'first philosophy.' In this regard, Aristotle defined Ontology as the science of being such that "all the species of being *qua* being and the attributes of which belong to it *qua* being" (Aristotle, Metaphysics IV, I as cited in Guarino and Giaretta (1995)). In addition, Aristotle identified modes of being, which evolved into categories to classify all things in the world such as substance, quality, quantity, person...(Gómez-Pérez et al., 2004).

In the same light, Bunge (1977) stated that metaphysicians are devoted to finding “unity in diversity, pattern in disorder and structure in the amorphous heap of phenomena” however the author made no clear distinction between metaphysics and ontology opting to use the terms interchangeably. Conversely, Smith (2003) exposed the subtle differentiation between metaphysics and Ontology where the author stated that metaphysics aims to determine which ontologies are indeed close to reality. Consequently, Ontology determines the construct of reality based on ‘what is’ in terms of its structure of objects, properties, events, processes and relations aimed at providing general categories of reality (Smith, 2003). According to Grimm et al. (2007), these general categories are called universals and the entities to be ordered based on these universals are referred to as particulars. This idea of universals was heavily debated post Aristotle in the Middle Ages resulting into two schools of thought: realism and nominalism (Gómez-Pérez et al., 2004). However, the point of inflexion within Ontology occurred in the Modern Age with Kant’s categorization of reality, which was based on one’s mental construct of reality (Gómez-Pérez et al., 2004). Consequently, Kant identified four main categories: quantity, quality, relation and modality.

Within Ontology, there exists several ideologies pertaining to the classification of entities for example, susbstantialism, fluxism, adequatist and reductionist. This philosophical discipline is overladen with its own complexity issues stemming from the same question that constitutes its DNA i.e. ‘what is’ ranging from questions surrounding its ontological commitment to its meta-level ontology. The purpose here is not to delve into the different schools of Ontology nor its complexities but rather to recognise the origins of ontology and its fundamental construct that pervades ontology use in computer science. One of the underlying philosophical contributions to computer science was that of Formal Ontology by Husserl which was defined as “the systematic, formal, axiomatic development of the logic of all forms and modes of being” (Cocchiarella (1991) as cited in (Gómez-Pérez et al., 2004, p. 5)). Guarino (1995) pointed out that this notion takes into account both sides of the coin i.e. formal logic (computer science) on one side and forms of being (philosophy) on the other and as such interpreted its meaning as the “rigorous description of [individual] forms.”

Conversely, ontologies are engineering artifacts (Guarino, 1998) that aid in elucidating the ‘Tower of Babel’ problem that occurs amongst the knowledge sharing community (Smith, 2003). The Tower of Babel problem that Smith referred to can be reduced to the issue of semantics across research that hinders the interoperability of information systems. Analogously, Noy and McGuinness (2001) identified that an ontology establishes a lexicon to be shared amongst researchers of a domain to either enable: i) sharing of the structure of information among computer agents as well as people; ii) re-use of domain knowledge, explicit domain assumptions; iii) separation of domain knowledge from operational knowledge and/or iv) analysis of domain knowledge. Kollarits and Wergles (2009) recognised further usages of ontologies that entailed facilitating knowledge management and making meaning explicit within a domain. With regards to the geo-fields, ontologies have been used to improve access and sharing of geographic resources (Kuhn, 2001).

Unlike its philosophical counterpart that is tied to being, ontologies in computer science have been attributed to a formal theory. The most cited and fundamental notion of ontologies was presented by Gruber (1993) who defined an ontology as “an explicit specification of a conceptualization.” The author drew a juxtaposition to philosophy stating that what exists in the computer science sense is the knowledge that can be represented formally, which is known as the universe of discourse. However, Uschold and King (1995) commented that Gruber’s definition left room for interpretation. A meticulous evaluation of the concept was undertaken by Guarino and Giaretta (1995) wherein the authors aimed to disambiguate the various specializations of ontology to arrive at a clear embodiment of the term for all related knowledge sharing communities. Here, Guarino and Giaretta (1995) used Gruber’s definition as the starting point of their analysis. The authors decomposed the notion of ontology into three senses: i) ontology as a conceptualization which reflects its semantic structure; ii) ontology as an ontological theory which underscores the logical theory of the knowledge being represented and iii) ontology as a specification of an ontological commitment. Guarino and Giaretta’s (1995, p. 31) notion of ontology went beyond Gruber’s interpretation and was defined as “a logical theory that gives an explicit partial account of a conceptualization.” It is this view of an ontology, which the scientific work beholds in developing a formal theory for resilience.

Following Guarino and Giaretta other notions surfaced over the years. In Smith’s (2003) description of ontologies in information systems, the author defined an ontology as “a dictionary of terms formulated in a canonical syntax and with commonly accepted definitions designed to yield a lexical or taxonomical framework for knowledge-representation which can be shared[...]it is a formal theory within which not only definitions but also a supporting framework of axioms is included.” This concept of ontology bore similar attributes to Guarino’s refined notion in his publication *Formal Ontology and Information Systems.* As Guarino (1998, p. 4) stated an ontology refers to “a hierarchy of concepts related by subsumption relationships [and] in more sophisticated cases suitable axioms are added in order to express other relationships between concepts and to constrain their intended interpretation.” These concepts bring into focus a further distinction amongst ontologies in computer science i.e. the characterization of ontologies as being lightweight or heavyweight. Lightweight ontologies refer to ontologies that capture a taxonomical or hierarchical structure of concepts in a domain whereas heavyweight ontologies go beyond the taxonomic level to define relations between concepts and impose axioms to add rigidity to the structure (Gómez-Pérez et al., 2004).

This section presented an overview of ontology making a clear distinction between the philosophical discipline and the method use in computer science and knowledge sharing fields. Ontology (capitalised ‘O’) deals with the existence and essence of being whereas in computer science ontology (lowercase ‘o’) is an engineering artifact or more so a method to represent knowledge. With reference to the resilience ontology in which this work aims to produce, the notion of ontology held by Guarino and Giaretta (1995) was adopted in keeping with the bigger picture of a GIS based resilience application. There are various methods to develop an ontology whereby the overall process is referred to as ontology engineering. In the upcoming sections some of these methods are discussed with emphasis being placed on the METHONTOLOGY approach. As Gómez-Pérez et al. (2004) stated rhetorically ontology engineering represents a composite of old and new science since in one hand it refers to the philosophical underpinnings of existence (old science) while at the same time codifying the knowledge into some form of logic (new science).

2.4 Foundational Ontology: Descriptive Ontology for Linguistic and Cognitive Engineering

In ontology engineering, there are several categorizations of ontologies based on their role to fulfil by the scientist. These ontologies are classified into four main types forming an ontology stack: application ontology, domain ontology, task ontology and top-level ontology (Figure 2.2). Commencing at the bottom of the stack, an application ontology consists of specialized vocabulary needed to define tasks that an application is required to perform by making use of the domain and task ontologies (Grimm et al., 2007). Conversely, domain ontologies consist of the vocabulary related to a particular domain of interest, in this case resilience, whereas task ontologies specify the general activities relating to the domain of interest (Guarino, 1998). According to Gómez-Pérez et al. (2004), such ontologies enable re-use within the discipline specified but not applicable across disciplines. In ontology design, vernacular inconsistencies within the field of interest are dealt with by employing a top-level ontology that provides the foundation from which terms in a knowledge base can be classified. This foundational ontology provides very general categories of how things in the world should be modelled based on existing knowledge (Masolo et al., 2003). Furthermore, the minimalistic nature of the foundational ontology makes it of particular interest in this research as it serves the role of aligning the resilience ontology. Here, the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) was used as the top-level ontology.

In DOLCE, things in the world are classified into four main categories i.e. Endurant, Perdurant, Quality and Abstract. There is a unique distinction between an endurant and a perdurant in this foundational ontology. This difference is temporal in nature. According

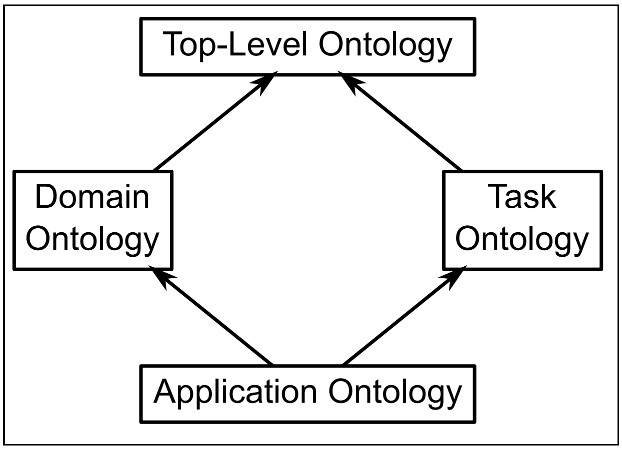

Figure 2.2: The Ontology Stack (Guarino, 1998).

to Gangemi et al. (2003, p. 18), "endurants are entities that are in time and lack temporal parts" whereas "perdurants are entities that happen in time and have temporal parts." In DOLCE, an endurant is present in its entirety at a particular point in time, however their properties may exhibit change over a period for example, persons within a community that forms a system. On the other hand, perdurants are partly present at a particular point in time for example, a hurricane. Qualities are entities that can be perceived or measured (Masolo et al., 2003), for example, resilience. Finally, DOLCE considers abstracts as entities that are not qualities and do not possess temporal nor spatial qualities (Masolo et al., 2003). Figure 2.3 shows a partial taxonomic illustration of the DOLCE categories. In addition to the basic categories, DOLCE also provides basic primitive relations for things. These relations typify entities within an ontology. The relations used for the resilience ontology are tabulated in Table 2.1.

Table 2.1: DOLCE Relations (Masolo et al., 2003) used in the Resilience Ontology.

Primitive Relation	**Category**	**Description**	**Example**

Is-A	Subclass	This primitive describes a hierarchical relationship that occurs between a super-class (entity) and a sub-class (entity) usually occurring in taxonomies. Here, the sub-class inherits the properties of the super-class.	A socio-ecological system Is-A system. Here the super-class is 'system' and the sub-class is 'socio-ecological system.'
Parthood	Mereology	DOLCE describes two types of parthood relation: 1) A-temporal; 2) Time-indexed. A-temporal relation exists for perdurants i.e. "entities that do not change in time" (Masolo et al., 2003). Consequently, time-indexed relation exists for endurants since "it is necessary to know when the relation holds" because an endurant can "loose or gain parts throughout its life" (Masolo et al., 2003, p. 20).	Adaptation is a-temporal-part-of Coping Strategy. Coping Strategy has various parts that a system can display such as adaptation, absorption and resistance.

Specifically-constantly-dependent-on	Dependence	This primitive relation is dependent on both modality and time i.e. "a particular x is specifically constantly dependent on a particular y iff at any time t, x cannot be present at t unless y is present at t" (Masolo et al., 2003, p. 21).	Resilience is specifically-constantly-dependent-on a Coping Strategy. Resilience of a system cannot be present unless there is a Coping Strategy in place at a particular point in time.
Has-quality/Inherent-in	Inherence	The inherence relation is used to describe qualities and their respective host.	A Socio-ecological system Has-quality Resilience.

2.5 Operationalization Through Semantic Reference Systems

The process of operationalization is an important step to a clear understanding of a concept. Operationalization entails the physical and mental measurement of a concept relative to a reference framework (Bridgeman, 1927). To make a concept operational means taking the idea from an abstract state into a form that is measureable. To make a concept measureable implies creating a reference frame for the notion for example, the concept of weight only becomes operational when the reference frame of kilogram is applied. Resilience is one concept that lacks formalization as well as operationalization (Klein et al., 2003). Drawing on the idea of semantic reference systems by (Kuhn, 2003), ontologies can be used to provide a reference frame for resilience.

The idea of semantic reference systems is centred around ontologies while at the same time hinges on the concept of geographic reference systems. In this regard, a semantic reference system uses an ontology as a reference frame to make explicit the meaning of geographic data, enables translation of meaning as well as allows for data integration (Kuhn and Raubal,

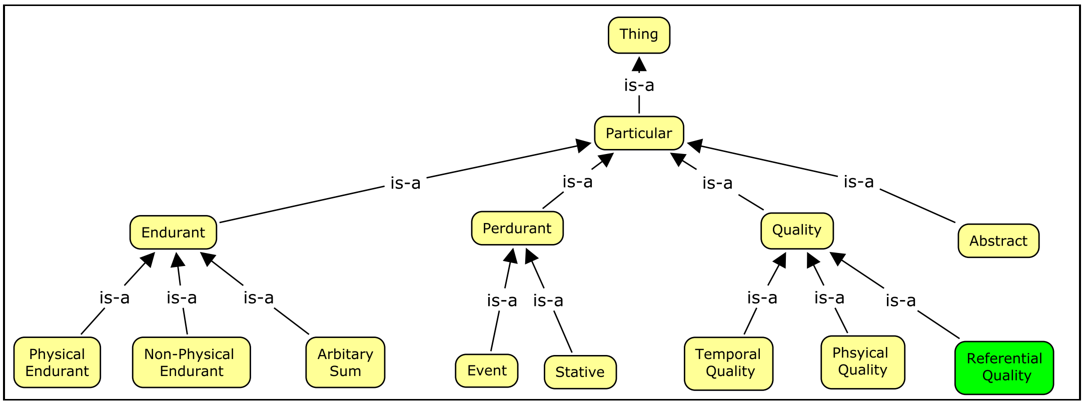

Figure 2.3: A Partial Taxonomy of the DOLCE Categories (Masolo et al., 2003). The green box represents the proposed category-referential quality-for modelling concepts such as resilience.

2003). According to Kuhn and Raubal (2003), a semantic reference system has two integral components: i) a semantic datum which grounds the concepts for example, semantics defined within a formal language or ontologies outside the structure and ii) semantic reference frame which "defines the conceptualization underlying the use of terms in a data model." Here, the foundational ontology or top-level ontology plays the role of a semantic reference frame. Moreover, Kuhn and Raubal (2003) identified the loose manner in which ontologies are constructed without being taken in reference to foundational ontologies. As such, the authors lobbied the need for ontology construction to be integrated within the semantic reference system framework. In this sense, a semantic reference frame is a viable approach to make concepts operational.

2.6 Ontology Engineering

As stated previously, the operationalization of resilience is hindered by the irregularities amongst definitions. Consequently, the use of ontologies can lend itself to stem the conceptual issues that occur in research. By rule of thumb, a domain ontology is constituted by the following components: classes, relations, formal axioms and instances. Classes define the concepts of a domain, for example, within resilience the concept *socio-ecological system* exists. Relations describe the formal affiliations between concepts, for example *socio-ecological system (class) is a type of (relation) system (class).* Formal axioms model sentences that are always true and are used to check the consistency of the ontology (Gómez-Pérez et al., 2004). Instances represent individual elements within a class, for example the *socio-ecological system of Port of Spain* is an instance of the class *socio-ecological system.* When each aforementioned phase is noted in detail and pieced together then the overall ontology is formed.

Ontology Design Process

Before one can delve into defining relations and logical representations, it should be acknowledged that there is a methodical flow to the overall ontology design process. This design process enumerates the activities that are warranted for the development of a domain ontology, which are dynamic and proliferated through a series of phases that constitute the life cycle of an ontology. It is erroneous to construct an ontology without considering the basic questions such as: 'What is the purpose of the ontology?' and 'Who are the intended users?' Fernández-López et al. (1997) roughly outlined nine activities that should be considered when developing an ontology. These activities included (Fernández-López et al., 1997):

- Planning: In planning the construction process, one determines the resources, time and tasks that would be needed to fulfil the ontology development.

- Specification: The developer provides answers to the aforementioned basic questions and notes it in an ontology requirements specification document.

- Knowledge Acquisition: In this phase knowledge for a particular domain is gathered both from primary and secondary sources. This process can extend throughout the ontology process.

- Conceptualization: Here, the knowledge gained in the previous activity is transformed into a conceptual model i.e. concepts and relations.

- Formalization: The conceptual model is taken from its natural language form and translated into a logical language for e.g. first order logic or description logic.

- Integration: This phase encourages developers to integrate existing ontologies with their own whenever it is possible. This reduces the workload of the developer since he/she does not have to start from scratch. For the resilience ontology, the use of content Ontology Design Patterns (ODP) presented by Gangemi (2005) was adapted to model resilience as a referential quality (see chapter 5).

- Implementation: The implementation activity involves the coding of the ontology in an ontology software that is able to check the consistency of the ontology.

- Evaluation: The evaluation entails the technical assessment of the ontology that includes verification and validation of the ontology.

- Documentation: Here, the developer notes down the steps performed in the construction of the ontology. Documentation thus extends throughout the design process.

- Maintenance: Maintaining the ontology entails the developer updating and modifying the knowledge encoded whenever necessary. Similar to the Documentation and Knowledge Acquisition phases, Maintenance should be executed throughout the design process.

Similarly, Gómez-Pérez et al. (2004) corroborated that there is a design process attached to ontology engineering. The authors also identified a similar list of activities, which were categorized into three main groups: Ontology Management Activities, Ontology Development Oriented Activities and Ontology Support Activities. There is no hard and fast ordering within the cycle as some steps (Support Activities) are executed throughout the entire process. Nonetheless, these steps act as a measuring stick and should be adhered to as closely as possible.

Attached to the design process are methods to go about achieving the activities outlined above. Such methodologies include Uschold and King's method, KACTUS and METHONTOLOGY to name a few. The first ontology approach was devised by Uschold and King (1995) that stemmed from their work on enterprise ontology. Conversely, the KACTUS methodology was birthed from the European ESPRIT project, with the focus on the development of methods and tools to facilitate knowledge re-use in technical systems (Schreiber et al., 1995). On the other hand, METHONTOLOGY originated from software development and knowledge engineering methodologies, which enables ontology building from the knowledge level (Gómez-Pérez et al., 2004). Since the ontology under construction is based on resilience knowledge with the purpose of disambiguating and making explicit the concepts and relations of its entities then it was considered apt to follow the METHONTOLOGY approach.

METHONTOLOGY offers a meticulous approach to develop ontologies from the knowledge level. This method rests on the shoulders of the ontology design process identified by Fernández-López et al. (1997). METHONTOLOGY was chosen as the backbone for the ontology construction based on the aforementioned qualities together with its iterative approach that enables integration of other ontologies, in this case, the content ontology design pattern for referential qualities. According to Gómez-Pérez et al. (2004), METHONTOLOGY allows for 'evolving prototypes' as revisions can be made to the ontology with each iteration or new 'prototype'. This is of particular interest especially if the ontology is to be further developed towards a resilience application. For this scientific work, the METHONTOLOGY approach undertaken was adapted from both Fernández-López et al. (1997) and Gómez-Pérez et al. (2004) to meet the needs of the research. Apart from following the overall flow of the design process, the foundational ontology, DOLCE was incorporated to align the resilience ontology. In this way, the resilience ontology transcends into a reference frame, in keeping with Kuhn and Raubal's (2003) call for ontology development within a theory of semantic reference systems.

Planning

The Planning phase marks the first step in the ontology design process. From the onset, the goal of the author was clear. This goal was birthed from the problem identified in resilience research as it pertains to climate change. The scope of the research is therefore not to re-define resilience but to lay the foundation towards operationalization through the development of a formal theory for resilience. In this sense, an ontology can provide a basis for development of a resilience application in geographic information systems while at the same time working through the conceptual blockage of the notion in order to formalize the concept of resilience. This ontology is geared towards the climate change domain where there is a stated need for information systems that can assess resilience in face of climate variability (ICSU, 2010).

With the intent of the ontology being known, the direction of the ontology was planned. In order to structure the notion of resilience, it was obvious that domain knowledge had to be gathered. In addition, the steps required to realize the resilience ontology had to be determined such as: identifying a glossary of terms, specifying relations, dealing with the quandary that presents itself when modeling qualities such as resilience in DOLCE as well as the logic language for formalization (either frame logic, first order logic or description logic). Furthermore, the choice of software for implementation had to be considered. Protégé [1] was chosen as the appropriate environment for implementation since it was free and provided a user friendly interface to input concepts and relations but more importantly a sound reasoner to check for inconsistencies such as circularity and partition errors that can occur. The time frame to complete the work was computed and milestones were therefore set for each task.

2.7 Conclusion

In this chapter, the formal theory approach was discussed. The reader was exposed to the notion of knowledge and ontologies and how both concepts go hand in hand. For this research, a

[1] Protégé is an ontology development software and is available for free at http://protege.stanford.edu/

knowledge engineering perspective is adopted to create the formal theory for resilience. Here, the knowledge encoded in the ontology is based on the writer's interpretation of resilience put forward by experts. The ontology engineering process outlined serves as the vehicle to transpose this knowledge into a logical theory. The METHONTOLOGY approach is applied to construct the resilience ontology while DOLCE is used as the foundational ontology to align it. In this sense, the ontology transcends into a reference frame in keeping with the theory of semantic reference framework. The planning phase was presented in this chapter, which marked the first activity of the ontology design process. The remainder of the thesis is structured according to the ontology design process commencing with the knowledge acquisition activity in Chapter 3.

Chapter 3

Knowledge Acquisition

There is an unrelenting devotion to using the concept [resilience] and an unquestioning, almost naive acceptance that resilience is good and must be promoted...Klein et al. (2003).

3.1 Introduction

The Knowledge Acquisition phase marks the second step in ontology engineering. It plays a pivotal role in the design process as it lays the foundation from which all concepts and relations are derived. This chapter is divided into two sections: i) A Review of the Resilience Concept and ii) The Disambiguation of Resilience. The first section delves into literatures across disciplines that pertain to resilience while at the same time establishing a knowledge base for the resilience ontology. Here, a collage of notions is presented in a chronological order together with its contextual constructs. The delimitations of resilience described in this chapter underline the epistemic tension that exists in its discourse. As a result, definitional issues surface resulting in several metaphors of resilience, which inhibits its formalization, operationalization and integration with vulnerability assessments. Through the disambiguation process, the concept is decomposed into tenets that represent the most general entities which are necessary to describe a system as having resilience.

3.2 A Review of the Resilience Concept

Resilience was first introduced by Holling (1973) in ecological research. The pertinence of the concept was unmasked, quickly becoming a fundamental notion in ecology and one of the most debated concepts across disciplines. Here, Holling noted the dichotomy that existed between resilience and stability in ecosystems.

> Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variable, driving variables, and parameters and still persist (Holling, 1973, p. 17).

On the other hand, Holling defined stability as "the ability of a system to return to a state of equilibrium after a temporary disturbance" wherein a system can have fluctuations but display resilience (Holling, 1973, p. 17). Comparably, Pimm's (1984) notion of resilience was birthed from his work on complexity and stability of ecosystems. In attempts to sort the complexity-stability paradigm within ecological research at that time, Pimm (1984) noted resilience as a variable of stability. The author defined stability as:

> A system is stable if and only if the variables all return to the initial equilibrium following their being perturbed from it.[...] The set of all values of the variables from which the system returns to a particular equilibrium is known as the domain of attraction (Pimm, 1984, p. 322).

According to Pimm (1984, p. 322), resilience of an ecosystem is a measure of "the speed of which the variables return towards their equilibrium from a perturbation" adding that stable systems "will often but not always be resilient the more complex they are" (Pimm, 1984, p. 324). In addition to stability, resilience was also discussed in relation to diversity. Whether or not diversity of the ecosystem enhances resilience is not known for certain as there are separate views regarding this matter. Theoretically speaking, Pimm (1984) stated that an increase in species reduces the resilience of the system, however the more connected the species are the greater the resilience of the system. Contrary to Pimm, Adger (2000) cited that researchers such as Schulze and Mooney (1994), Mooney and Ehrlich (1997) and Tilman (1997) suggested that diversity of the ecosystem enhances its resilience and stability. Nonetheless, one certainty is that ecological resilience relates to the functioning of an ecosystem in face of a disturbance (Adger, 2000).

From its origins in ecology, the notion of resilience has transcended across domains. It has been deemed an essential concept not only in ecology but also in sustainability science (Handmer and Dovers, 1996; Adger, 2000), disaster management (Klein et al., 2003) and climate change (Klein, 2002) due to the underlying social importance placed on ecological systems. In Handmer and Dovers *A typology of Resilience: Rethinking Institutions for Sustainable Development*, the authors devised a typology of resilience based on the institutions that govern the interaction of systems. Their research aimed to disambiguate the hindrances to sustainability and or sustainable development within societies. It was considered that at the core of sustainability is the ability of systems both human and natural to cope with the uncertainty surrounding change, a characteristic of a system known as resilience, drawing on the concept of resilience from both ecological and risk studies. In essence, resilience as it pertains to sustainability relates to "how a system copes with major perturbations to its operating environment" (Handmer and Dovers, 1996, p. 486).

In the same breath, Handmer and Dovers (1996) stated that resilience in risk management relates to the preservation of daily activities within communities and their welfare. This notion is reflective of resilience in Psychology. Waller acknowledged that the study of resilience emerged from the area of risk. In dealing with pervasive risks and uncertainty that occur between systems, Handmer and Dovers (1996) specified two forms of resilience that a system can portray. This definition created a new dimension of resilience wherein the concept is placed on a continuum with proactive and reactive resilience being at the extreme ends of the scale. Reactive and proactive resilience were described as follows:

> A system that develops a reactive approach to resilience does this by strengthening its status quo and making the current system resistant to change whereas a system that establish a proactive method to resilience accepts the inevitability of change and attempts to create a system that is capable of adapting to new conditions and imperatives (Handmer and Dovers, 1996, p. 494).

Transitioning into Disaster Management, Kendra and Wachtendorf (2003) defined resilience as "the ability to respond to singular or unique events." Furthermore the authors brought into focus another salient resilience dichotomy put forward by Wildavsky (1988) wherein resilience was contrasted with anticipation. Wildavsky (1988, p. 77) stated that:

> Anticipation is a mode of control by a central mind; efforts are made to predict and prevent potential damages before damage is done whereby resilience is the capacity to cope with unanticipated dangers after they have manifest, learning to bounce back[...]anticipation attempts to avoid hypothesized hazards whereas resilience is concerned with those that have been realised.

In Wildavsky's discussion of resilience and anticipation, the author shed light on the disparity that exists in choosing an approach to secure safety within a society. Two questions were brought into focus addressing this imbalance. Firstly, is it in the best interest of society to rely solely on anticipatory measures that can lead to negative multiplier effects throughout a system or secondly is it in the best interest to cope with disasters as they unfold (Wildavsky, 1988)? Additionally, the author drew a juxtaposition between his notion of anticipation and resilience with Holling's dichotomy of stability and resilience. In this regard, anticipation was viewed as a means of cultivating stability while resilience, on the other hand, fosters the accommodation of variability. A pertinent observation was made concerning Holling's definition of resilience as it applied to securing safety. Wildavsky (1988) stated that maintaining a continuous state of safety may be detrimental to a system since it reduces the ability of the system to cope with disasters in the long-run. Adjacent to this claim, was the observation made by Miller et al. (2010) with regards to climate change. It was cited by the authors that research into resilience of rural communities in face of climate variability in Africa revealed that maintaining a current state effectively allows society to cope with a particular stress but cripples development and sustainability of the system for example, through the lack of innovation and technology by the society. Therefore the maintenance of a state decreases resilience of a system in the long-run. Nonetheless Wildavsky (1988) suggested that there is room for both resilience and anticipation in securing safety since both entities have desirable attributes and the use of their measures depends on the circumstances of the hazard.

From a geographical perspective, Adger (2000) took the resilience dilemma one step further as he aimed to explore whether or not a relation existed between ecological and social resilience by examining system interactions within a coastal zone. The author defined social resilience as "the ability of communities to cope with external stresses and disturbances resulting from social, political and environmental change" whereas he described ecological resilience as "a characteristic of ecosystems to maintain itself in face of disturbance" (Adger, 2000, p. 347). The link between both concepts lies in the dependency of society on the ecosystem, which reiterates DeGroot's (1992) ecosystem functions. This dependency is governed by institutions, which constitute the social fabric of society. Thus the linking factor between social and ecological resilience is the presence of institutions that includes everything from the norms and values of societies to stakeholders and government organisations that provide legal systems and distribute property rights to regulate resources (Adger, 2000). This link was shown in the author's case study of mangrove conversion and management in Vietnam.

As highlighted in Adger (2000), the symbiotic relationship of society and ecosystem brought into focus two other key concepts amidst the resilience discussion: vulnerability and criticality, where social vulnerability was described as "the exposure of groups of people or individuals to stress as a result of environmental change" and criticality referred to "the extent of environmental degradation that precludes the continuation of current use systems and levels of human well-being given feasible adaptations and societal capabilities to respond" (Adger, 2000, p. 348) It is this acknowledgement of stress within an environment that illustrates the resilience of a system. (Adger, 2000) stated that stress is pervasive and related to the nature of the social and economic structures that underpin society. Similarly, risk factors identified by Waller can also be classified as stressors that influences the resilience of an individual and by extension a community. In this forum, resilience was defined as the positive adaptation to adversity (Waller). From a psychological standpoint, Waller further noted the non-static nature as well as alluded to the context-specific nature of resilience, adding that resilience is not an innate trait of the human system and at different periods an individual may respond differently to the same stress i.e. being resilient to one event but vulnerable to another. Though stress impedes positive adaptational outcomes, protective factors could act as a buffer between these stressors and the lives of individuals (Waller).

Adger's investigation of resilience also touched on the term 'coping strategies', a variable that would later form part of the ontology in the subsequent chapters. In his evaluation of resilience use cases, coping strategies were viewed as tactics taken in face of food insecurity (threat). These strategies undertaken by the African and Indian sample populace were catered towards preserving future income and consumption rather than maintaining their current state. Adger (2000) acknowledged that these adjustments led to a new vulnerability state to future food security dilemmas. Correspondingly, Daniel and Ortmann (2011) identified coping strategies as central to resilience with these strategies having four mechanisms: withstand, maintain, absorb and adapt that lend to a process of coping wherein a system could undergo each phase over time. More importantly, (Adger, 2000) made known the indicators of social resilience which encompassed the economic situation of society, environmental variability, stability and migration and mobility of population and stressed that indicators have to be considered collectively since observation of one would not give the full picture of resilience.

With reference to climate change, resilience was linked to the concept of vulnerability. Resilience and vulnerability are notions that are complementary in nature, dynamically linked through socio-ecological system interactions in face of disturbances. In this regard, Timmerman (1981) (as cited in Klein et al. (2003, p. 39)) defined resilience as "the measure of a system or part of a system's capacity to absorb and recover from the occurrence of a hazardous event." Since Timmerman, other researchers also have tied resilience to vulnerability. Mimura (1999) and Klein and Nicholls (1999) both recognized the importance of resilience in determining vulnerability. Mimura (1999, p. 141) stated that "determining vulnerability lies in the balance between the susceptibility of the system and its resilience." Furthermore, Klein and Nicholls (1999) corroborated this view by suggesting that resilience of a system be incorporated in the Intergovernmental Panel on Climate Change (IPCC) Common Methodology for vulnerability assessments. This is evident that resilience is not the absence of vulnerability (Waller). Additionally, Pelling (2003, p. 48) considered resilience as one of three components (the others being exposure and resistance) of vulnerability to natural hazards wherein resilience to natural disasters was described as "the ability of an actor to cope with or adapt to hazard stress." In the same light, Turner et al. (2003) (as cited in Miller et al. (2010)) also considered resilience as one dimension of vulnerability assessment with the other two components being exposure and sensitivity. According to Petersen (2007), a Resilience Framework can decrease a system's exposure to a disaster, decrease its sensitivity in terms of planning and increase the adaptive capacity that is the ability of the system to learn from its experience. This ideology of a Resilience Framework as an effective tool to mitigate the risk of disaster from climate induced sea level rise was also proposed by Sutherland et al. (2004).

One of the salient milestones in the resilience academic debate was the acknowledgement of the inter-relation that exists between human and ecological systems and the coining of the term socio-ecological system (SES) by Berkes et al. (2000). This paved the way for the initiation of the concept socio-ecological system resilience and the distinction within the concept between 'specified' and 'general' resilience. According to Miller et al. (2010), specified resilience refers to resilience of a SES with respect to a singular event i.e. "resilience of what to what" (as cited in Carpenter et al. (2001) whereas general resilience relates to "resilience of all aspects of a system to unspecified, including novel and unforeseen, disturbances." For example, the resilience of corn production to drought represents an instance of specific resilience, however making production resilient only to drought may leave the system vulnerable to other threats. The significance of resilience was further sealed with the formation of the Resilience Alliance, a group of scientists aimed at executing resilience research to support sustainable development policies (Klein, 2002). The Resilience Alliance defined resilience of a SES as having three dimensions (Klein, 2002, p. 17):

> The amount of disturbance a system can absorb and still remain within the same state or domain of attraction; The degree to which the system is capable of self-organisation; The degree to which the system can build and increase the capacity for learning and adaptation.

This description of resilience is reminiscent of the typology of resilience shared by Handmer and Dovers (1996) wherein the authors described resilience as having three types:

- Type 1-Resistance and Maintenance: Here, a system challenges the uncertainty that encompasses environmental issues and does whatever it can to evade changes to its structure to deal with the uncertainty. For hazards that are certain, the system employs anticipatory measures. The authors further stated that this method is preferred by authority figures since it sustains their drive for power. The inflexibility of the system has both advantages and drawbacks. The advantages of a resistant system are that it fosters stability within the social system as it attempts to preserve its domain of attraction; resources are employed at their optimal potential (in the short-run) and it prevents maladpatation to occur in the system. Consequently, the drawbacks entail the inability to adjust to changes which can lead to irreversible damages to the system resulting in a lack of long-term sustainability and the eventual demise of the system. According to Handmer and Dovers (1996), type 1 resilience was evident during the 1970s in the United States where hesitance was expressed in dealing with ozone depletion immediately until there was definite proof.

- Type 2-Change at the Margins: In this form of resilience, the system concedes to the uncertainty attached to environmental problems and their implications and as a result puts into effect plans to enable changes to the system. This is an advantage of type 2 resilience. The authors stated that such changes are incremental and made at the margins of the system in order not to "challenge the basis of society." These changes treat the symptoms of the threat, which can be seen as a disadvantage to the system . Furthermore, it fosters "a false sense of security" within society as changes are made. According to Handmer and Dovers (1996), type 2 resilience was evident in Toronto's decision to deal with climate change in the 1990s by reducing greenhouse gas emissions by 20% even though the IPCC suggested that 60% reduction in emissions was required to stabilize is atmospheric composition at that time.

- Type 3-Openness and Adaptability: This type of resilience goes directly to the cause of the problem. The system embraces uncertainty and is prepared to adapt by making necessary changes to the system. In this sense, the system is less susceptible to disturbances because of its flexibility to change. As a result, an open and adaptable system would foster sustainability in the long-run. The aforementioned characteristics highlights the benefits of such a system, however, the drawbacks of adaptability include the occurrence of instability as well as the possibility of maladaptation within the system. According to Handmer and Dovers (1996), adaptation has been evident in Australia by the aboriginal society, which has learnt overtime to become ecologically sustainable with respect to climate change.

Akin to the Resilience Alliance, the United Nations International Strategy for Disaster Reduction (UN/ISDR) recognised the pertinence of resilience in dealing with natural hazards and disaster management. Here, resilience was defined as:

> The capacity of a system, community or society to resist or to change in order that it may obtain an acceptable level in functioning and structure. This is determined by the degree to which the social system is capable of organizing itself and the ability to increase its capacity for learning and adaptation, including the capacity to recover from a disaster (Klein et al., 2003, p. 41).

Following the theory of resilience, researchers of the last decade began casting a critical eye on past definitions as they relate to the current environment. One such publication was Klein et al. (2003) wherein the authors investigated the notion of resilience as it applied to megacities in face of natural disasters. It was their view that definitions, which incorporated a system returning to an equilibrium state are antiquated as it applied to megacities and disasters. The reason being the a system's original state prior to a disaster implies a vulnerable position held by it, thus reverting to this original state post-disaster indicates returning to its vulnerable position (Klein et al., 2003). This perspective makes sense and could be extended to resilience and climate change as societies aim to achieve longevity amid environmental variability with the aim of reducing its vulnerability to the exposure. According to Klein et al. (2003), concepts that include self-organization, learning capacity and adaptation are desirable since it promotes the idea of recovery by the system. Here, the authors established a link between resilience and adaptation.

Concomitantly, Manyena (2006) also assessed the pertinence of resilience in disaster management discourse. The author introduced the concept of disaster resilience and its role in disaster management. This form of resilience was conceived as being a buffer between the system and hazard in order to ensure minimum damage. Disaster resilience was thus defined as:

> The intrinsic capacity of a system, community or society predisposed to a shock or stress to adapt and survive by changing its non-essential attributes and rebuilding itself (Manyena, 2006, p. 446).

However, the author made known the befuddlement that occurs with resilience due to definitional issues on the conceptual level. Manyena (2006) stated that though resilience can aid in vulnerability and risk reduction, the idea of resilience in the realm of disaster management should encompass human capacity far beyond the minimum standards of coping. In addition, the author highlighted that resilience defined on the basic guidelines of development is not a sufficient embodiment of the notion since it does not establishes the desire of individuals to be away from danger zones. Similar to Klein's assessment, it was conceded that definitions of resilience that incorporate the notion of adaptation could be pertinent to policy formation since it relates to strategy creation that can minimize future vulnerability to disasters (Manyena, 2006).

At present, resilience research is centred on developing linkages between resilience and vulnerability. The focus here is to build on the strengths of each concept in order to inform theoretical work, practical assessments and policy formation as it pertains to socio-ecological systems in face of environmental changes (Miller et al., 2010; Turner et al., 2010). Noting the complementary nature of resilience and vulnerability, Miller et al. (2010) discussed the need for integration of both concepts on the conceptual, technical and policy level to foster sustainable development. According to the authors, one domain that recognizes this integration is the field of the disaster risk reduction where vulnerability to hazards is of utmost concern. Here, resilience was defined as having three dimensions:

> The ability to absorb shocks; The ability to bounce back; The ability to learn and adapt (Ahmed, 2006, as cited in (Miller et al., 2010)).

Nonetheless, the authors acknowledged that despite the use of the concept in the aforementioned domain, a breakdown transpires between the application of resilience in reality and resilience on the conceptual level. In other words, there is a need to transmute resilience thinking to a practical entity in the real world.

Conversely, Folke et al. (2010) were concerned with the linkages of resilience to the notions of adaptability and transformability. In his publication, the authors aimed to develop a theoretical resilience framework in order to bring awareness to socio-ecological system dynamics and engender resilience thinking. At the core of this proposed framework is the inter-relationship of resilience, adaptability and transformability, which is hinged on social change. The idea of Folke's resilience thinking is to breakthrough the current notion of resilience that encourages persistence and to induce embracing resilience as the interaction of persistence, adaptability and transformability to foster sustainability. Furthermore, the resilience framework should enable research in the direction of SES, their thresholds and regime shifts. In this regard, Folke et al. (2010) considered resilience as "the tendency of a SES subject to change to remain within a stability domain, continually changing and adapting yet remaining within critical thresholds."

In summary, several abstractions of resilience were presented. Together with this notion, other relevant concepts surfaced such as vulnerability, sustainability and adaptation. The common thread amongst these concepts is that resilience permeates each one. Notwithstanding, what was observed through the compilation of literatures was the multiplicity of definitions and contention that exists across disciplines with each domain creating its respective take on resilience. Despite the conflict, these domains gave validation to the term as each acknowledged the latent potential of the concept in dealing with the uncertainty of climate change, natural disasters and risk reduction. Nevertheless, there are several hindrances that occur in resilience research. There is an apparent breakdown in communication between the theoretical and the application side of resilience research that hinders development of resilience knowledge and its application in the aforementioned domains to reduce risks and foster sustainability (Miller et al., 2010; Manyena, 2006).

Digressing to the theoretical side of resilience, one challenge that surfaced is the communication issues that arise due to the plethora of definitions that clouds conceptual work on resilience. According to authors, there were various meanings imbued within the concept of resilience (Miller et al., 2010; Manyena, 2006). As Klein et al. (2003, p. 42) puts it "after thirty years of academic analysis and debate the definition of resilience has become so broad as to render it almost meaningless." Other researchers considered this dilemma as having the ripe possibility for future research and conceptual development. It was Klein et al. (2003) who pointed out the need for the concept of resilience to be formalized and made into an operational definition so that resilience thinking could be translated into an implementable entity for policy and management purposes. Being cognizant of the bottleneck that occurs on the conceptual level, this scientific work therefore hinges on Klein's thought of operationalization. The notions reviewed in this section provided a vast insight into resilience while at the same time providing a rich knowledge base for ontology engineering. Furthermore, the literature gathered played a quintessential role in the disambiguation activity presented in the subsequent section.

3.3 Disambiguating Resilience

From the knowledge acquisition phase, the notions of resilience were disambiguated and the knowledge required to populate the ontology was derived. A manual text mining of literatures was undertaken, which spanned various disciplines (as discussed in Section 3.2) and also provided a secondary means to gather experts' opinions on resilience. Usually in the ontology building process, developers employ an automatic linguistic classification tool to crawl through numerous data to identify concepts and definitions for their ontology (see for example, Velardi et al. (2001); Jiang et al. (2003); Taylor et al. (2007)). However, the shortcoming of this method is that one does not gather contextual knowledge surrounding the choice and usage of definitions proposed by researchers. As a result, it was in the interest of the author to gather the contextual knowledge that encompasses resilience since it is a complex concept grounded in ecology. To properly represent this notion, the factors and processes that play into resilience needed to be understood. In addition to secondary sources of information, informal meetings were held with experts in the geo-field to gain some insight into their perspectives of resilience based on their line of research.[1] These discussions also helped shape the author's contextual knowledge of resilience.

The concepts discussed in the previous section were dissected in order to arrive at a common denominator of resilience. The definitions were correlated against each other to determine the degree of overlap or divergence. From the evaluation, five key tenets of resilience were identified: *ability, system, cope, external factor* and *bounce back*. Existing concepts refer to a *system* that constitutes both social and ecological entities coined socio-ecological system. This system has been described as having a particular *ability* or capacity to do something as it pertains to resilience. The ability to do something is related to the ability to manage or deal via some mechanism with an external factor unto the system, which is denoted as *cope*. The *external factor* is a generalization of the stress, disturbance or perturbation that threatens

[1]Informal discussions were held with Dr. Dr. h.c. Gilberto Câmara, Director of Brazil's National Institute for Space Research on April 29th 2011 as well Dr. Chris Renschler of the University of Buffalo on July 13th 2011.

the system. However, its qualification as undermining the system makes it synonymous to a stress or threat. The latter definitions of resilience included the function of recovery by the system from a disturbance that is characterized by the tenet *bouncing back*. Thus, it can be deduced that resilience in its most general form can be defined as:

> *The ability of a system to cope with an external factor that undermines it, with the system bouncing back.*

This definition formed the basis of the ontology as a reference frame for resilience and fulfils the first objective of the thesis .

From the evaluation, it was reckoned that the idea of coping is the central component of resilience. According to the Waite et al. (2006), to cope means to “effectively deal with something.” From the concepts examined, the idea of dealing or handling of stress by a system has been conveyed in the use of the words such as:

- absorb (Holling, 1973; Timmerman, 1981; Klein, 2002; Ahmed, 2006)
- resist (Handmer and Dovers, 1996; Adger, 2000; UN/ISDR, 2004)
- withstand (Adger, 2000)
- adapt (Handmer and Dovers, 1996; Waller; Pelling, 2003; Turner et al., 2003; UN/ISDR, 2004; Manyena, 2006; Ahmed, 2006; Folke et al., 2010)
- self-organize (Klein, 2002; UN/ISDR, 2004)
- maintain (Adger, 2000)
- return (Pimm, 1984)
- remain (Folke et al., 2010)

These words describe actions taken by the system to deal with stress and can be viewed as strategies of coping. However, some specializations of cope are more related than others. Withstand and resist are terms synonymous with each other. To withstand or resist a disturbance implies keeping out the disturbance from the system as much as possible, before the disturbance occurs. On the other hand, absorb suggests an amount of disturbance a system could take in before changes in its structure take place. To adapt to a disturbance suggests changes made to the structure of the system to minimize potential damage. These adjustments are based on the system's experiences and lessons learnt in dealing with climate induced changes (Burton et al., 2001). Self-organization could be deemed as part of the process of adaptation wherein the system alters its structure in face of a particular threat. Maintain, return and remain have been linked to preserving a particular state of the system i.e. the system does not transform to a new state. This type of coping strategy counteracts current resilience thinking geared towards promoting transformability and adaptability in face of climate induced changes. As stated previously, Klein et al. (2003) indicated that returning to the original state means going back to a vulnerable position whereas Miller et al. (2010) stated that maintaining a current state thwarts innovation and makes the system less resilient in the long-run. These types of coping strategies are therefore not conducive for reducing a system's vulnerability. Thus the specializations of coping could be summarized into four strategies: withstand, absorb, adapt and maintain.

To evaluate the potency of the general definition formulated above, the established definitions of the Resilience Alliance and the United Nations International Strategy for Disaster Reduction (UN/ISDR) were examined to see how well they fitted into the general structure (Table 3.1). From the assessments, it can be stated that the generic definition is a good umbrella abstraction of resilience befitting of the concepts discussed.[2]

[2] Section 3.3 was adapted from Daniel and Ortmann's (2011) work on the disambiguation of resilience.

Table 3.1: Comparison of Disambiguated Definition to Established Definitions.

Disambiguated Definition	**Specialized Definition**	**Comments**
The ability of a system to cope with an external factor that undermines it, with the system bouncing back.	Resilience Alliance: The amount of disturbance a system can absorb and still remain within the same state or domain of attraction; The degree to which the system is capable of self- organisation; The degree to which the system can build and increase the capacity for learning and adaptation (Klein, 2002).	The definition fits well with the general take on resilience since the key elements are identifiable within its structure wherein each dimension indicates one strategy of coping.
The ability of a system to cope with an external factor that undermines it, with the system bouncing back.	UN/ISDR (2004): The capacity of a system, community or society to resist or to change in order that it may obtain an acceptable level in functioning and structure. This is determined by the degree to which the social system is capable of organizing itself and the ability to increase its capacity for learning and adaptation, including the capacity to recover from a disaster.	There are two dimensions to the definition. Overall, both parts of the definition fit well with the disambiguated version. However, in the second dimension a particular system is specified. If the "degree to which a system is capable of organizing itself..." is one way of describing the resilience of a system then this part of the definition implies that social resilience determines the overall resilience of a system. This reiterates the link that social resilience and ecological resilience systems share via institutions and management of resources (Adger, 2000).

3.4 Conclusion

To conclude this chapter, it would be apt to quote Stibbs (1988) (as cited in Manyena (2006, p. 436)): “words are prisons as well as searchlights and pigeonholes for what we see.” This statement sums up the main issue that plagues resilience research i.e. the definitional conundrum caused by the continuous re-invention of the concept across disciplines. The review of the resilience theories marked the first phase in acquiring knowledge for the ontology. Based on the notions presented, resilience was disambiguated and a general definition of resilience derived. Here, resilience was deduced as: *The ability of a system to cope with an external factor that undermines it, with the system bouncing back.* The aim of this scientific work is not to present a new definition of resilience but rather a formal theory of the concept. Therefore it was mandatory that a general definition was inferred in order for a logical representation of resilience to be conceptualized in the following chapters.

Chapter 4

Conceptualization

A conceptualization is an intensional semantic structure which encodes the implicit rules constraining the structure of a piece of reality (Guarino and Giaretta, 1995).

4.1 Introduction

In this chapter, the conceptualization phase of the design process is presented. This phase symbolizes the start of the physical construction of the ontology and its quality depends on the vastness of knowledge attained in the previous activity. Stepping into the "quagmire of logic and philosophy" of knowledge engineering (McDermott (1993) as cited in Guarino (1995)), the entities that constitute resilience and their relations can formally be made explicit. In the METHONTOLOGY approach, this is done via a set of immediate representations, which are detailed tasks used to transmute knowledge into a semi-formal state (Gómez-Pérez et al., 2004). Since providing a formal theory of resilience is the overarching goal of this research, not all immediate representations were applicable. As such, the process was adapted to the project requirements and the following representations were employed:

1. The creation of a Glossary of Terms.
2. A Taxonomic Representation of Resilience.
3. The illustration of Ad Hoc Binary Relations.
4. The creation of a Concept Dictionary.
5. The description of Ad hoc Binary Relations.
6. The description of Axioms.

4.1.1 Glossary of Terms

The glossary of terms represents a lists of concepts, relations, attributes and descriptions that are incorporated in an ontology. For the resilience ontology, the decomposed tenets of resilience (discussed in Section 3.3) formed the concepts in the ontology. The relations defined in the glossary are rooted in DOLCE and specified for the concepts in the ontology. Table 4.1 contains a partial glossary of terms. A full list of terms is provided in the Appendix.

Table 4.1: Glossary of Terms Used in the Resilience Ontology

Name	**Associations**	**Acronym**	**Description**	**Type**
External Factor	Threat; Stress; Disturbance	-	Stimuli that occurs outside of the system, which undermines the system and has a damage potential attached.	Concept

System	-	-	Complex interaction of elements with these interactions specifying a particular relation between elements (von Bertalanffy, 1950).	Concept
Socio-ecological System	-	SES	Complex interaction of elements that constitute both the social and ecological systems specifying the interlinkages between both systems (adapted from (von Bertalanffy, 1950).	Concept
Ability	-	-	The capacity of the system to do something (Waite et al., 2006).	Concept
Coping Strategy	-	-	Mechanisms used to effectively manage or deal with an external factor (adapted from (Waite et al., 2006)).	Concept

4.1.2 Taxonomy

A taxonomy represents a hierarchical structure of the concepts listed in the glossary of terms, which have a superclass-subclass relationship. This relationship implies inheritance meaning that any property and instance of the superclass are inevitably passed on to the subclass.

From the Glossary of Terms, one taxonomy was identified wherein the *socio-ecological system* concept is deemed a subclass of the concept *system* and is illustrated in Figure 4.1.

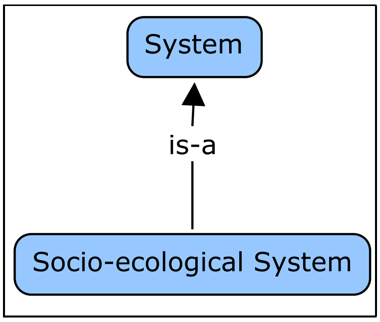

Figure 4.1: Taxonomic Relation within Resilience.

4.1.3 Ad Hoc Binary Relations Diagram

In this activity, the relations between all the concepts were specified with the aid of Cmap Tools[1]. By visualizing the concepts, it facilitated the establishment of linkages between concepts. The DOLCE relations (Table 2.1) were used to define the binary relationships between the terms. Figure 4.3 illustrates the conceptual map of resilience.

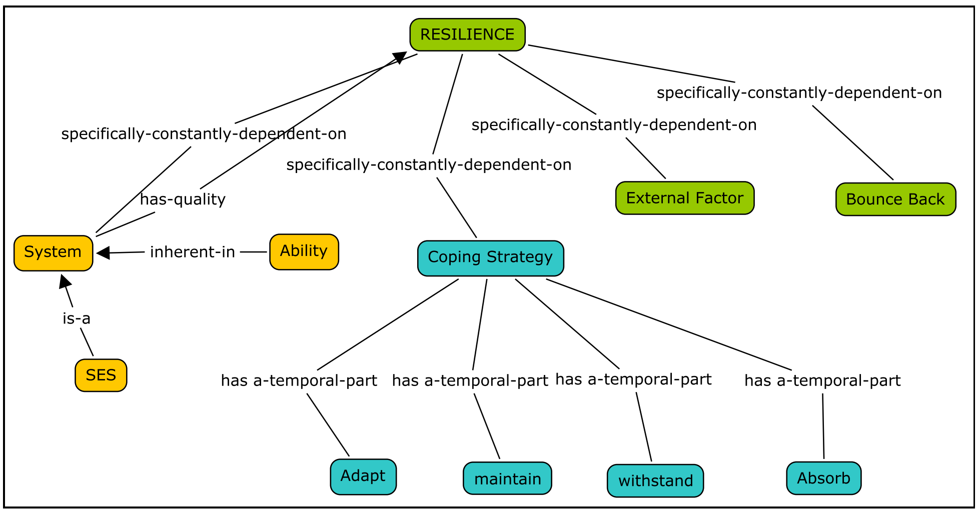

Figure 4.2: Ad hoc Binary Relations Diagram.

[1] Cmap Tools is a software used to create concept maps and is available for free at `http://cmap.ihmc.us/download/`

4.1.4 Concept Dictionary

The concept dictionary for resilience ascertained the concepts as well as the binary relations that will be included in the ontology and implemented. Table 4.2 gives a description of these concepts and their relations (both forward and inverse relations) in the dictionary.

Table 4.2: Concept Dictionary for Resilience

Concept Name	**Relations**
System	has type
Socio-ecological System	is type of
Coping Strategy	specific-constant-dependence; specifically-constantly-dependent-on
Adapt	has-a-temporal-part; is-a-temporal-part-of
Maintain	has-a-temporal-part; is-a-temporal-part-of
Withstand	has-a-temporal-part; is-a-temporal-part-of
Absorb	has-a-temporal-part; is-a-temporal-part-of
External Factor	specific-constant-dependence; specifically-constantly-dependent-on
Bounce Back	specific-constant-dependence; specifically-constantly-dependent-on
Ability	inheres
Resilience	has quality; is quality of

4.1.5 Ad Hoc Binary Table

The ad hoc binary table represents a refinement of the concept dictionary established above. In this activity, relations were meticulously paired with their source and target concepts while mathematical properties were defined for each concept as illustrated in Table 4.3

Table 4.3: Ad Hoc Binary Table for Resilience

Relation Name	**Source Concept**	**Target Concept**	**Math. Properties**	**Inv. Relations**
has type	System	Socio-ecological System	Transitive	is type of
specific constant dependence	Coping Strategy	Resilience	-	specifically-constantly-dependent-on
specific constant dependence	External Factor	Resilience	-	specifically-constant-dependence-on
is quality of	Ability	System	Transitive	has quality
specific constant dependence	Bounce Back	Resilience	-	specifically-constantly-dependence-on
is a-temporal part of	Adapt	Coping Strategy	Transitive, Symmetric	has a-temporal-part
is a-temporal part of	Maintain	Coping Strategy	Transitive, Symmetric	has a-temporal-part

is a-temporal part of	Withstand	Coping Strategy	Transitive, Symmetric	has a-temporal-part
is a-temporal part of	Absorb	Coping Strategy	Transitive, Symmetric	has a-temporal-part
has quality	System	Resilience	Transitive	is quality of

4.1.6 Defining Formal Axioms

An axiom is a statement, which is "declaratively and rigorously represented knowledge that has to be accepted without proof" (Mizoguchi and Ikeda, 1998). Its main purpose is to verify the consistency of the knowledge contained in the ontology (Gómez-Pérez et al., 2004). Based on the disambiguation process, the following statements were declared to constrain the interpretation of resilience in the ontology. The axioms are presented (Tables 4.4, 4.5 and 4.6.) in first order logic and follow the METHONTOLOGY format described by Gómez-Pérez et al. (2004).

Table 4.4: Axiom 1: Resilience of a system

Axiom Name	Resilience of a system
Description	Resilience is a quality of the system and is dependent on an external factor.

Expression	forall (?R) and [system](?S) and [external factor] (?X) and [is-a-quality-of](?R, ?S) and [dependent-on](?R, ?X)
Concepts	System, Resilience, External Factor
Ad hoc Relations	specifically constantly dependent on, is-a-quality-of
Variables	?S, ?R, ?X

Table 4.5: Axiom 2: Coping ability of a system

Axiom Name	Coping ability of a system
Description	For resilience, there exists a system that has the ability, which is dependent on a particular coping strategy.
Expression	forall (?R) and [resilience](?R) there exists (?S, ?A, ?C) and [system](?S) and [ability](?A) and[coping strategy] (?C) and [has-quality](?S, ?R) and [has-quality](?S, ?A) and [dependent-on](?C, ?A)
Concepts	System, Ability, Coping Strategy
Ad hoc Relations	specifically constantly dependent on, has quality

Variables	?S, ?A, ?C

Table 4.6: Axiom 3: Coping strategy of a system

Axiom Name	Coping strategy of a system
Description	Resilience is dependent on a particular coping strategy i.e. withstand or absorb or adapt or maintain taking place over a time.
Expression	forall (?R) and [resilience](?R) there exists [coping strategy](?C) and ((there exists [withstand](?W) and [withstand](?W) and [has-a-temporal-part] (?C, ?W)) or (there exists [absorb](?Y) and [absorb](?Y) and [has-a-temporal-part] (?C, ?Y)) or (there exists [adapt](?Z) and [adapt](?Z) and [has-a-temporal-part] (?C, ?Z)) or (there exists [maintain](?M) and [maintain](?M) and [has-a-temporal-part] (?C, ?M))

Concepts	Resilience, Coping Strategy, Withstand, Absorb, Adapt, Maintain
Ad hoc Relations	specifically-constantly-dependent-on, has-a-temporal-part
Variables	?R, ?C, ?W, ?Y, ?Z, ?M

4.2 Content Ontology Design Pattern for Resilience

In keeping with the idea of operationalization through a semantic reference frame (see Section 2.5), the alignment of the resilience ontology to DOLCE is carried out in this section. During the conceptualization process, it was established that resilience is a quality of a system that is dependent on an external factor. In this sense, resilience does not simply inhere in one host but is often taken with reference to another entity, usually an externality. For example, the resilience of a coastal system cannot be assessed without taking into consideration an external factor such as sea level rise or an earthquake event. In trying to align the conceptual model with DOLCE, the author unearthed the predicament of modelling resilience under the foundational ontology. In DOLCE, qualities inhere only in one entity, however, resilience requires two entities to be perceived: i) a host entity (system) and ii) a referent entity (external factor). To overcome this shortcoming, the author was involved in the creation of an ontology design pattern for referential qualities (Ortmann and Daniel, 2011) to facilitate the implementation of the resilience ontology with DOLCE. Thus, the authors proposed a new category for DOLCE called *referential quality*, as indicated in Figure 2.3.

In Philosophy, several classifications of qualities exist. Two such denominations are non-relational and relational qualities wherein the former refers to qualities that inhere only in one entity and the latter to qualities that inhere in more than one entity (Weatherson, 2006). However, only the former can be modelled in DOLCE and follows a unique pattern that entails an Endurant, Quality, Quale, Space (EQQS) (Figure 5.1) as described in Masolo and

Borgo (2005). In this pattern, the *endurant* (E) serves as the host for the *quality* (Q), with a *quale* (Q) being located in a *quality-space* (S) (Masolo et al., 2003). Take for example two persons having the same weight. In DOLCE, each person has his/her own distinct weight quality. This distinction account for changes, for example, if one person gains or looses weight. Operationalization of the qualities occurs via the quale. The quale is the value ascribed to the quality and it describes the position of the quality in a quality space (Masolo et al., 2003) whereas the quality space would be the metric space for weight. Conversely, the DOLCE pattern described above does not compensate for modelling relational qualities. For example, the solubility of a substance in a liquid cannot be replicated in the EQQS pattern because the solubility inheres in both the substance and the liquid. Thus, qualities that are dependent on two entities, such as resilience, fall short of this pattern.

Content Ontology Design Patterns are modular structures in ontologies. According to Gangemi and Presutti (2009, p. 231), these patterns are "distinguished ontologies that address a specific set of competency problems[...]and show certain characteristics [such as being] computational, small, autonomous, hierarchical and cognitively relevant." Gangemi (2005) introduced a frame for implementing content design patterns, which includes in its blueprint a generic design pattern, local design pattern, logic formulation, reference ontology, composed design pattern, formal relation, axiomatization of the pattern, description of the pattern, encoding as well as a Unified Modelling Language (UML) representation of the pattern.

To address the shortcoming of modelling resilience with DOLCE, the existing quality pattern discussed above was extended to include a reference entity. Hence, resilience was coined a referential quality since it always relies on a referent in order to perceive its existence. This can also be said for its sibling concept vulnerability. The referential quality pattern was defined as EQRQS with an endurant (E) serving as the host of the quality (Q), a referent entity (R) and a quale (Q) being located in a quality-space (S) (Figure 5.2). The pattern is general enough to enable modelling of concepts that essentially have one host but is dependent on a reference entity. Hence, the generic case can be stated as a quality *Q of an entity X taken with reference to another entity R.* This pattern should suffice to account for resilience, which is

Table 4.7: Glossary of Concepts used in the Ontology Design Pattern for Referential Qualities Formalization

Concept	Symbol
Endurant	ED
Quality	Q
Quale	QL
has quale	ql
Referent	R
specifically-constantly-dependent-on	iscd
Referential Quality	RQ

always dependent on an external factor. The pattern was also found useful to model the ability of the system. As a result, the pattern is found extensively throughout the formalization of resilience.

The ontology design pattern for referential qualities was formalized in Description Logic[2]. The glossary of concepts used in the formalization is provided in Table 5.1.[3]

The pattern was expressed as:

$$RQ \equiv Q \sqcap \exists \text{ inheres . } ED \sqcap \exists \text{ iscd . } R \sqcap \exists \text{ ql . } QL$$

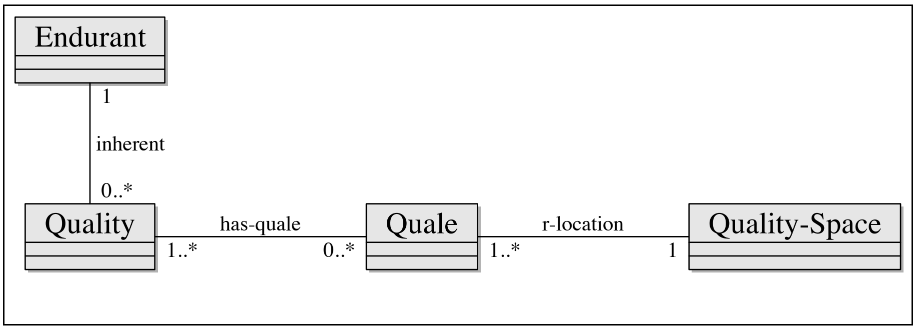

Figure 4.3: DOLCE Quality Pattern-EQQS (Ortmann and Daniel, 2011).

[2]Description Logic (DL) is a formal language that is used to describe knowledge base and enable reasoning about this base (Nardi and Brachman, 2003).

[3]Section 4.2 was adapted from Ortmann and Daniel's (2011) work done on content ontology design pattern for referential qualities.

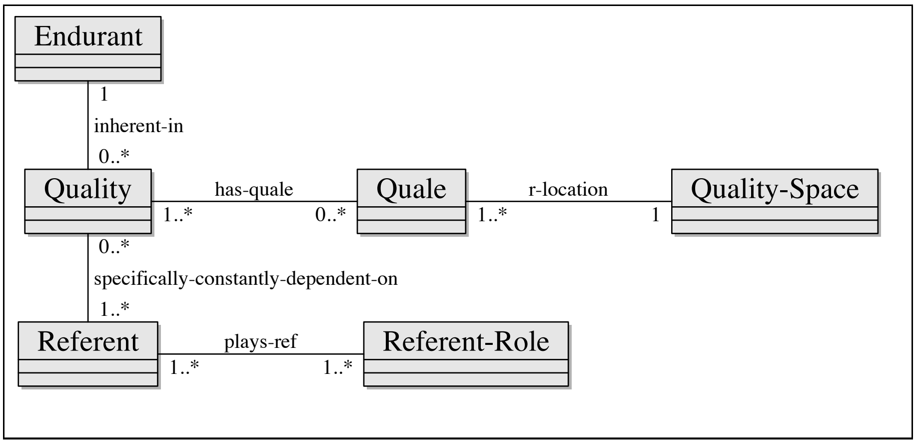

Figure 4.4: Content Ontology Design Pattern for Referential Qualities-EQRQS(Ortmann and Daniel, 2011).

4.3 Conclusion

This chapter meticulously described the conceptualization process of the resilience ontology. The conceptualization phase is integral to the ontology design process since it is responsible for the structuring of knowledge contained within an ontology. Here, the resilience knowledge was taken from an abstract to a semi-formal state via a series of immediate representations. As each activity came together, the conceptual model for resilience was birthed.

Usually, once the conceptual model is developed, implementation of the model follows. A predicament occurred in trying to align the conceptual model with DOLCE. In DOLCE, qualities inhere in one entity, however, resilience requires two entities to be perceived. To overcome this challenge, the author was involved in the creation of a content ontology design pattern for referential qualities (Ortmann and Daniel, 2011). Here, the DOLCE pattern for qualities (EQQS) was expanded to incorporate entities that inhere in one host but also reliant on a referent. As a result, the *referential quality* category was birthed and denoted by the pattern EQRQS. With the physical construction of the ontology is completed, the following chapter set forth the formal theory of resilience deduced via the ontology design process.

Chapter 5

The Formal Theory of Resilience

An ontology is a logical theory that gives an explicit partial account of a conceptualization (Guarino and Giaretta, 1995).

5.1 Introduction

In trying to arrive at a formal theory for resilience, Description Logic (DL), Attributive Concept Language $\mathcal{ALC}$ was used as the formal system of choice to codify the assertions made in the conceptual model. In Description Logics, a distinction is made between TBox and ABox knowledge. A knowledge base is made up of both a TBox and ABox wherein the former describes intensional knowledge or general knowledge that is depicted via declarations about the concepts within the base (Nardi and Brachman, 2003). On the other hand, the latter describes extensional knowledge or assertional knowledge that relates to the individuals within the ontology (Nardi and Brachman, 2003). In the resilience ontology, intensional knowledge is the only form of knowledge represented since its purpose is to tackle the communication issues surrounding the resilience concept.

Table 5.1: Logical Symbols and their Descriptions adapted from(Baader and Nutt, 2003)

Symbol	Descriptions
$\top$	Universal concept i.e. the super concept of all concepts.
$\bot$	Bottom concept i.e the opposite of the universal concept.
$C \sqcap D$	The intersection of the concepts C and D.
$C \sqcup D$	The union of the concepts C and D.
$\neg C$	Not concept C.
$\forall R.C$	Universal quantification.
$\exists R.C$	Existential quantification.
$C \sqsubseteq D$	Concept inclusion i.e. C is a subclass of D.

Table 5.2: Glossary of Concepts contained in the Formalization

Concept	Symbol
Resilience	RES
System	SYS
System participating in coping	SYS'
Ability	ABY
Coping Strategy	CS
Adapt	ADT
Maintain	MT
Withstand	WT
Absorb	ABB
External Factor	EF
Bouncing Back	BB

5.2 Formalizing Resilience

This section describes the steps taken to formalize resilience using Description Logic. For the readers that may be unfamiliar with DL $\mathcal{ALC}$, Table 5.1 provides an explanation of the symbol notation (which is rooted in set theory) used in the formal theory of resilience. In addition, Table 5.2 gives a glossary of concept, which occur in the formalization while Tables 5.3 and 5.4 furnish the readers with a list of DOLCE categories and relations present in the the theory.

Table 5.3: Glossary of DOLCE Categories Contained in the Formalization (adapted from Masolo et al. (2003))

Category	Symbol
Arbitrary Sum	AS
Process	PRO
Quality	Q
Referential Quality	RQ
Endurant	ED
Perdurant	PD

.

Table 5.4: Glossary of DOLCE Relations Contained in the Formalization (adapted from (Masolo et al., 2003))

Relation	Symbol
has-quality	qt
is-quality-of	iqt (inverse relation of qt)
specific-constant-dependence	scd
specifically-constantly-dependent on	iscd (inverse relation of scd)
has-temporal-part	pt
has-damage-potential	dp

.

Signature Definition

A signature[1] in Description Logics is defined as $\Sigma = (\mathbb{C}, \mathbb{R}, \mathbb{I})$, where $\mathbb{C}$ is a set of all concept names, $\mathbb{R}$ is a set of all relation names and $\mathbb{I}$ is a set of all individual names.

According to Table 5.2, the following signature can be defined for the resilience ontology (RO):

$$\begin{aligned}
\mathbb{C}_{RO} &= \{RES, SYS, SYS', ABY, CS, ADT, WD, MT, ABB, EF, BB, AS, PRO, Q, RQ, ED, PD\} \\
\mathbb{R}_{RO} &= \{qt, scd, pt\} \\
\mathbb{I}_{RO} &= \{\} \\
\Sigma_{RO} &= (\mathbb{C}_{RO}, \mathbb{R}_{RO}, \mathbb{I}_{RO})
\end{aligned}$$

All symbols (both concepts and relations) to be included in the formalization have been introduced. The following section provides the formalization of resilience.

[1] A signature contains all non-logical symbols defined by the user, for example the names of concepts, roles and individuals.

5.3 Resilience TBox

Based on the above specifications, the TBox for the resilience ontology is given by:

$$RES \sqsubseteq RQ \tag{5.1}$$

$$SYS \sqsubseteq AS \tag{5.2}$$

$$ABT \sqsubseteq RQ \tag{5.3}$$

$$EF \sqsubseteq \exists dp.Q \tag{5.4}$$

$$BB \sqsubseteq PRO \tag{5.5}$$

$$RQ \equiv Q \sqcap \exists scd.\top(ED \sqcup PD \sqcup Q) \tag{5.6}$$

The following axioms express the disjointness between the parts of the coping strategies:

$$ADT \sqcap MT \sqsubseteq \perp \tag{5.7}$$

$$ADT \sqcap WD \sqsubseteq \perp \tag{5.8}$$

$$ADT \sqcap ABB \sqsubseteq \perp \tag{5.9}$$

$$MT \sqcap WD \sqsubseteq \perp \tag{5.10}$$

$$MT \sqcap ABB \sqsubseteq \perp \tag{5.11}$$

$$WD \sqcap ABB \sqsubseteq \perp \tag{5.12}$$

Formal Definition of Resilience

Recall the general resilience definition:

The ability of a system to cope with an external factor that undermines it, with the system bouncing back.

In the conceptual model, concept relations were predominantly described based on mereology i.e. the theory of part-whole relations as well as dependence. Additionally, the inherence relation was utilized to specify qualities that inhere in entities. In the model, it was stated that resilience is a *quality* because it can be measured within the system. In DOLCE qualities are entities, which can be perceived or measured (Masolo et al., 2003). From the resilience knowledge gathered, this quality occurs when faced with a disturbance or stressors in the environment. Hence, it was deemed that resilience is *specifically-constantly-dependent-on* an external factor in order to be realized. Here, the dependence relation was used to describe an entity (external factor), which is required for resilience to occur. In other words, resilience could only be present if and only if an external factor is present at the same time. Consequently, the resilience axiom was declared as:

Resilience is a quality of a system and is dependent on an external factor.

This axiom can be formally expressed as:

$$RES \equiv RQ \sqcap \exists qt.SYS' \sqcap \exists scd.EF \tag{5.13}$$

Based on the disambiguation activity in Section 3.3, *coping* was determined to be at the core of a system's resilience. The system was also stated as having the ability (deemed as a quality of the system) to cope. For resilience, this ability is specifically-constantly-dependent-on the manifestation of one of the coping strategies identified in Section 3.3. As a result, the second axiom was reckoned:

A system has an ability which is dependent on a particular coping strategy.

The second axiom can be formally expressed as:

$$SYS' \equiv SYS \sqcap \exists qt.ABY \sqcap \exists iscd.CS \tag{5.14}$$

Finally, this coping strategy a system exhibits was conveyed through various terms in the resilience literature. From the definitions presented (Section 3.2), it was inferred that a system dealt with a disturbance by either choosing to adapt, withstand, absorb or maintain a current state. These actions were deduced as *coping strategies* that a system displays, after which the system bounces back. The DOLCE parthood relation was used to describe the entity *coping strategy* and its respective temporal parts as indicated in the third formalization.

> Resilience depends on a particular coping strategy i.e. withstand or absorb or adapt or maintain taking place over a time, with the system bouncing back.

The assertion made about the coping strategy can be formally expressed as:

$$CS \equiv PRO \sqcap \exists pt.(ABB \sqcup WD \sqcup MT \sqcup ADT) \sqcap \exists pt.BB \tag{5.15}$$

Substituting axiom (5.14) into (5.13) , resilience is formally defined as:

$$RES \equiv RQ \sqcap \exists iqt.(SYS' \sqcap \exists qt.ABY \sqcap \exists iscd.CS) \sqcap \exists iscd.EF \tag{5.16}$$

5.4 Implementation

One of the objectives of ontology engineering is to enable re-use of existing ontologies in order to reduce redundancy and double work in design. By employing the design pattern proposed above, the conceptual model was implemented into Protégé. Since the pattern is aligned to DOLCE Lite [2], it facilitated the alignment of the resilience ontology to the foundational

[2]DOLCE Lite is a Description Logic variant of DOLCE

ontology. The integration of the pattern into the resilience ontology validated the potency of the design pattern. All implementation was done in OWL-DL[3] and is publicly available[4].

Following the pattern, resilience was classified as a *referential quality* that inheres in a *system*. This system was qualified as an *endurant* under the DOLCE category *arbitrary-sum*. Abstracting from the governing and economic institutions, communities as well as ecosystems that make up a socio-ecological system, the system was treated as an entity that is made up of many endurants. As stated previously, resilience is always taken with reference to an external factor. This external factor can be classified as a threat, disturbance or stress, which has a *damage-potential* as its subclass. It is the damage-potential referent that resilience depends on, for example, a society has resilience to a hurricane event. It is not the hurricane event that a society will build its resilience on but the latent damage potential that the event possesses. This *damage-potential* qualification was based on the MONITOR Risk Ontology (Kollarits and Wergles, 2009) and considered as "the quality of an environment, which results from an event that is dependent on the value and vulnerability of the objects" in the environment. Since vulnerability and resilience have a symbiotic relationship i.e. building resilience reduces vulnerability to a particular threat then the referent, *damage-potential* from the risk ontology can be applied to the current resilience ontology. Here, the *damage-potential* was classified as a *quality* in Protégé. The quale for resilience was left unspecified since there are several factors that contribute to determine its value, which is outside the scope of the thesis. Consequently, the quality space was not stipulated since it is reliant on a resilience quale.

Likewise, the design pattern was also applied to model the ability of a system as a referential quality. In the conceptual model, it was deemed that the ability was inherent in the system and is *specifically-constantly-dependent-on* a *coping strategy* as a referent. This *coping strategy* was modelled as a *perdurant* under the DOLCE category *process*. This process has several temporal parts i.e. withstand, maintain, absorb and adapt that the system undergoes over

[3]OWL-DL is a description logic specialization of the web ontology language (OWL). For more information see: `http://www.w3.org/TR/2004/REC-owl-guide-20040210/#OwlVarieties`. Accessed on December 12 2011)

[4]`http://www.jensortmann.de/ontologies/resilience-ontology1.owl`

time as part of displaying resilience. In DOLCE, processes are deemed to be occurrences or happenings that are both cumulative and anti-homeomeric (Masolo et al., 2003). An occurrence is cumulative if it “holds of the mereological sum of two of its instances” (Masolo et al., 2003) for example, the sum of two instances of coping strategy is still part of the coping strategy. On the other hand, an occurrence is anti-homeomeric if “its temporal parts cannot be described by the same expression used for the whole occurrence” (Masolo et al., 2003) i.e. the individual parts of coping strategy cannot be given the same linguistic expression as the overall process (coping strategy).

Comparably, the entity *bouncing back*, which relates to the system's function of recovery was also classified as a perdurant under the DOLCE category achievement. A system's recovery from an external factor is a complex undertaking. It is made up of a series of activities that is generically-constantly-dependent on a shared plan amongst participants (Kollarits and Wergles, 2009). Abstracting from the specificities of bouncing back that underscores a system, the system's recovery was therefore treated as an achievement of the system. Additionally, the concepts *bouncing back, coping strategy, system and damage potential* were stipulated as each having a specific-constant-dependence to resilience. To illustrate the use of the pattern, the following instances were postulated in the implementation: *Port-of-Spain socio-ecological system, resilience to sea-level rise* and *sea-level-rise damage potential*. This was necessary to test the consistency of the OWL implementation. For the consistency check, the HermiT version 1.3.5 reasoner in Protégé[5].

5.5 Maintenance and Documentation

Maintenance and Documentation are activities that extend throughout the ontology engineering process. During the design process, the resilience knowledge encoded was updated when necessary and the steps taken to achieve fruition of the resilience ontology were noted

[5]HermiT is a reasoner used to check for consistencies within an ontology. See`http://hermit-reasoner.com/` for more information

and presented in this scientific work.

5.6 Conclusion

In this chapter, the formal theory of resilience was presented together with its implementation in Protégé. The formalization gives an explicit account of the semantics of resilience and straightens out the conceptual fuzziness, which clouds the practical usage of term. The formalization ascertains three salient characteristics of resilience: i) resilience is a quality of a system, ii) resilience is perceived when taken in reference to an external factor and iii) resilience is dependent on a coping strategy. The formal theory was implemented in Protégé with postulated instances.

Chapter 6

Evaluation

6.1 Introduction

This work is motivated by the definitional issues that underlie resilience research. To overcome the communication issues that permeate resilience research, a formal theory of resilience was created. The overarching goal was achieved through ontology engineering methods and formalized in Description Logic. This chapter evaluates the resilience ontology to determine whether the objectives outlined were achieved as well as to correlate the resilience formalization against the accepted conceptualizations put forward by the Resilience Alliance and the UN/ISDR.

6.2 Assessment of the Resilience Ontology

In ontology evaluation, a technical judgement of the ontology's content is undertaken (Gómez-Pérez et al., 2004). Usually, this entails verifying and validating the ontology to determine whether or not definitions are implemented correctly and the modelled world encoded in the ontology is congruent to reality (Gómez-Pérez et al., 2004). In a similar light, Burstein and

Gregor (1999) put forward a comprehensive set of guidelines to assess system development approaches, which encompass the validation and verification of its design process. Although these guidelines are endemic to system development, the criteria are general enough to be applied to ontology engineering. Both ontology engineering and system development share a computer science foundation and are utilized in information systems. The evaluation is subdivided into five categories each with its specific questions to judge the design process. These questions presented by Burstein and Gregor (1999) were tailored to the ontology research.

- Significance: What are the theoretical and practical significance of the research?
- Internal Validity: Does the methodology work?
- External Validity: Is the resilience ontology congruent with the knowledge in the domain of resilience? Are the findings applicable elsewhere?
- Objectivity/Confirmability: Is the ontology design process noted in detail? Are biases and assumption made during the design process made explicit?
- Reliability/Dependability: Is the research statement clearly stated? Are the basic constructs of the design process specified?

Significance. The ontology possesses both theoretical and practical significance in resilience research. The theoretical significance is attributed to the creation of the formal theory of resilience. The purpose of this research was motivated by the communication issues, which permeated resilience research. Consequently, a knowledge representation perspective was adopted to sort out this dilemma through ontology engineering. A resilience ontology was produced to structure the domain knowledge of resilience while at the same time provide a formalization of the concept. The design process went beyond specifying a vocabulary for resilience but showed salient linkages between entities, for example between resilience and adaptation, a concept that is also heavily researched in climate change. In the formal theory, the process of adaptation falls within the resilience framework as a type of coping strategy. The ontology gave an explicit semantic account of resilience as a means to curb the communication debacle fuelled by the continuous re-definition of the term in research.

On the other hand, the practical significance of the ontology design could be attributed to the implementation of the content ontology design pattern for referential design pattern created by Ortmann and Daniel (2011). This pattern was birthed to overcome the shortcomings of DOLCE in dealing with ecological concepts. It provided the resilience ontology with the paradigm needed for its alignment with DOLCE. This was facilitated via the simple extension of the DOLCE quality pattern (EQQS) to include a referent (EQRQS) in its pattern. Through the design pattern the resilience ontology transcended into a semantic reference frame for resilience. Moreover, it smooths out the ambiguities that were imbued in the concept and provides a common platform for researchers to establish consensus in meaning since the ontology is publicly available. The formal theory of resilience would facilitate computational assessments and dispenses a building block towards application development.

Internal Validity This scientific work did not propose a new approach in ontology engineering but employed an existing methodology to devise the formal theory of resilience. The METHONTOLOGY approach was chosen since it rests on the pillars of the ontology design process and enables ontology engineering from the knowledge level. Although the method was utilized in this research, the resilience ontology did not fully commit to it. In METHONTOLOGY, it is not mandatory for ontologies to be aligned to a foundational ontology. Since the efforts of this research is geared towards resilience operationalization, the theory of semantic reference frames (Kuhn, 2003) was incorporated. Here, the resilience ontology was aligned to DOLCE in order for the ontology to provide a semantic reference frame for resilience. To facilitate the alignment, the ontology design pattern for referential qualities was integrated in the ontology. The extensive use of the pattern in this research validates the potency of the pattern in dealing with concepts that are dependent on a referent under DOLCE. Tasks for specifying instances were omitted from the development process since it was not deemed pertinent to the formulation of a formalization. In the same breath, it can be contested that instances are necessary to test a formalization. Generally, instances are derived from data in the ontology engineering process, however, due to the dearth of data this was not possible. Instead, instances were postulated in the implementation phase to facilitate the consistency check of the ontology. These adjustments made to the methodology do not undermine the value of the methodology nor the consistency of the ontology. There are no hard and fast rules to create ontologies but general guidelines to govern the process.

External Validity. The external validity is evaluated based on how well the knowledge encoded in the theory matches the real world as well as the applicability of the resilience ontology research. To compare the modelled view of resilience to knowledge in the domain requires the opinions of resilience experts, however, due to time constraints this was not possible. Nonetheless, the concepts and relationships encoded in the ontology were deduced from knowledge put forward by experts across various disciplines. These notions were disambiguated and a general conceptualization of resilience was derived. It was ensured that the entities of the definition were broad enough to encompass the views expressed by these experts. The relations in the theory stemmed from DOLCE's basic primitive relations. The findings of the ontology is catered to those research fields, which are concerned with socio-ecological resilience and environmental change. On the other hand, the content ontology design pattern for referential qualities is applicable to all qualities that require a referent to be perceived and needs to be aligned to DOLCE. It should be stated that external validity of the resilience ontology would only come about when the ontology is re-used by other researchers.

Confirmability/Objectivity. The design process of the resilience ontology was meticulously documented and in so doing the path to formalization was made explicit. In this research, two biases presided over the ontology engineering process:

- Knowledge bias: The resilience ontology possesses a knowledge bias since it focuses on the socio-ecological concept of resilience. The knowledge gathered covered domains such as disaster management, sustainability and climate change that are fixated on socio-ecological system resilience. Although the ontology created is catered for the climate change domain, it is still general enough to transcend across other disciplines where socio-ecological systems research is of interest.

- Cognitive bias: There is a cognitive bias entwined into the resilience ontology. All relationships described between concepts were based on DOLCE's ontological structure of the world. This bias is further sealed with the commitment of the design pattern to DOLCE. The DOLCE ontology organizes the world into categories with relationships that are grounded in philosophy and cognitive science (see Masolo et al. (2003)).

Reliability/Dependability/Auditability. The research objectives for this research were clearly stated. The first objective entailed disambiguating the notion of resilience. A review of the concept across disciplines was undertaken and presented in this work. The various notions were decomposed into entities that formed a general definition of resilience. The decomposition process was based on secondary sources of knowledge. The second objective involved specifying the relationships between the entities of resilience. This was done in natural language using the DOLCE relations, which predominantly contained mereological and dependence relations. However, the complex interactions, which occur within the socio-ecological system, coping strategies and process of recovery were not examined and thus not formally defined in the ontology. Abstracting from their complexities, these entities were classified under the DOLCE categories *arbitrary-sum, process* and *achievement* respectively. However, the categorisation *arbitrary-sum* does not provide a sufficient embodiment of the concept *socio-ecological system.* Finally, the research aimed to formalize the notion of resilience. Here, axioms were specified to constrain the interpretation of resilience within the theory. The axioms were then translated into Description Logic and implemented using Protégé into OWL-DL. Due to the general knowledge represented in the conceptual model, rules could not have been deduced to analyse data and facilitate the creation of new knowledge.

Overall, these three objectives contributed to the creation of the formal theory of resilience. This formal theory thus: elucidates the concept of resilience; constrains the interpretation of the concept (which can limit the continuous re-invention of the wheel that occurs in resilience research) and is the precursor in the development of a computational resilience application.

6.3 Comparison of the Formal Theory to Resilience Conceptualizations in Research

In this section, the formalized definition of resilience is compared to the established conceptualizations put forward by the Resilience Alliance and the UN/ISDR. As a reminder, the formal theory of resilience defined resilience as:

$$\text{RES} \equiv \text{RQ} \sqcap \exists\ \text{iqt}\ .\ (\text{SYS'} \sqcap \exists\ \text{qt}\ .\ \text{ABY} \sqcap \exists\ \text{iscd}\ .\ \text{CS}) \sqcap \exists\ \text{iscd}\ .\ \text{EF}$$

where CS was defined as:

$$\text{CS} \equiv \text{PRO} \sqcap \exists\ \text{pt}\ .\ (\text{ABB} \sqcup \text{WD} \sqcup \text{MT} \sqcup \text{ADT}) \sqcap \exists\ \text{pt}\ .\ \text{BB}$$

The formalized definition is comprised of the following three tenets:

1. Resilience is a quality of a system dependent on an external factor.
2. The system has the ability to undergo a particular coping strategy.
3. The coping strategy entails the ability to adapt or withstand or absorb or maintain, from which the system recovers.

The Resilience Alliance (RA) defined resilience as:

> The amount of disturbance a system can absorb and still remain within the same state or domain of attraction; The degree to which the system is capable of self-organisation; The degree to which the system can build and increase the capacity for learning and adaptation (Klein, 2002).

At a glance, elements of the formalization can be noted in this definition. Both conceptualizations recognize the presence of an external factor (disturbance) as well as the ability to cope, which are required for resilience perceived. The first dimension of the RA's definition identifies the presence of an external factor while the ability to cope with a disturbance is conveyed in all three dimensions. Hence, it could be stated that the second tenet maps directly to the RA's definition while the first tenet only maps partially to it. The has-quality relation, which bonds the entities *system* and *resilience* is not embodied anywhere in the definition even though resilience is recognized as a characteristic of a system in research (see Chapter 3). A juxtaposition could be drawn here to the MONITOR project wherein the concept of vulnerability is modelled as part of their risk ontology. In the risk ontology, vulnerability was defined as "the quality of (objects of) the environment, which determines damage, given a defined (hazardous) event" (Kollarits and Wergles, 2009). If vulnerability and resilience are concepts that are complementary in nature and share a symbiotic relationship (i.e. increasing resilience reduces vulnerability), then the authors' assertion of vulnerability as a quality gives currency to the formal specification of resilience as a quality of a system in the resilience ontology.

Digressing into the third tenet of resilience, the concept *coping strategy* was established as the general term to describe the strategies a system may employ against an external factor. In the conceptualization phase, the concept *coping strategy* was deemed as having several temporal parts i.e. adapt or maintain or absorb or withstand, from which the system bounces back. These strategies do not share the same instances, for example, a strategy cannot be a mechanism to adapt as well as a form of maintenance at the same time. Due to the complexity of the strategies, their individual processes were not examined beyond the basic relation encoded in the formalization. However, the third tenet seems to be at odds with the RA's concept of resilience. Within the RA's definition, the following three coping strategies are acknowledged: absorb, remain (maintain) and adapt. The first dimension promotes persistence while the second and third encourages the system to learn and adapt in face of a disturbance.

Consequently, the internal conceptualizations could be considered antithetical to each other. In the first dimension, it is implied that the system tries to ensure that its current state is maintained as best as possible. Conversely, the second and third dimensions communicate the idea of transformation since self-organization and adaptation entail changes within the structure of the system as the system learns to creatively deal with a disturbance and moves into a new state. Researchers have indicated that maintaining a current state leads to the demise of overall and future resilience as it stunts transformation (see Adger (2000); Miller et al. (2010)). In addition, the action of recovery, denoted by the concept *bouncing back* in the ontology is not conveyed in the RA's definition. A system could enforce adjustments to its structure that causes it to maladapt and be worse off than its previous state thereby not regaining a healthy, functioning state. Overall, the resilience ontology unearthed discrepancies within the RA's conceptualization of resilience. Having opposing strategies within one conceptualization adds to the bemusement that surrounds the communication and practical usage of resilience in research. It is evident that the meaning of entities and relationship amongst entities were not considered in their construction of resilience.

The formal theory of resilience was also evaluated against the UN/ISDR conceptualization of resilience. The UN/ISDR defined resilience as:

> The capacity of a system, community or society to resist or to change in order that it may obtain an acceptable level in functioning and structure. This is determined by the degree to which the social system is capable of organizing itself and the ability to increase its capacity for learning and adaptation, including the capacity to recover from a disaster (UN/ISDR, 2004).

Akin to the RA's definition, the first tenet of the formal theory is partially represented in the UN/ISDR's conceptualization. This notion also fails to capture the basic axiomatic relationship between *resilience* and *system* i.e. resilience as a quality of a system. Nevertheless, the external factor (disaster) is acknowledged in the definition. The second tenet maps directly to the definition as the ability to cope via some mechanism is recognized. The third formalization is also evident in the definition as the ontological characterization of the coping strategies is noted within the UN notion of resilience. Here, the system either resists or changes but not both. The use of the term 'change' in the definition is presumed as referring to the coping strategy *adapt* since adaptation relates to changes in the system. In the second part of the definition the social system was specified as the determinant of the system's resilience. If the 'degree to which the system is capable of adaptation' is considered as a form of resilience then social resilience is responsible for the system's overall resilience. To validate whether social resilience determines a system's overall resilience goes outside the scope of this work but the meaning imbued in the second part of the definition makes for interesting future research. The UN/ISDR also recognizes recovery in their resilience definition, which the ontology establishes as necessary for resilience to be realized. In general, it can be stated that the UN/ISDR's definition shares the ontological underpinnings of the resilience formalization and thus there is a high degree of overlap between their definition and the conceptualization encoded in the resilience ontology.

6.4 Discussion

In face of climate change, societies have entered a slippery slope as environmental changes outrun mitigation efforts (ICSU, 2010). As such, the (ICSU, 2010) stated that in order to meet the challenges of climate change what is required are information systems that can facilitate data integration, analysis and modelling with one of its key functionalities being able to assess vulnerability and resilience. If such a feat is to be achieved then conceptual ambiguities need to be clarified. Without a clear meaning and more importantly a formalization of this meaning, domains concerned with resilience would continue to spend time re-defining the concept instead of forging ahead with its application development and operationalization. Emphasis therefore should be placed on further expanding the formalization as well as establishing inter-linkages between resilience and vulnerability within the formal framework. The formalization could then be tested within an agent based environment.

After reading this dissertation, some experts may question what are the other benefits of a formalization or more specifically a resilience ontology beyond making a concept clear. To some experts resilience may already be clear in their minds. However, what the evaluation has shown is that people's perceptions of a concept is not always straightforward as one thinks when written in natural language. Differences in conceptualizations of resilience leads to dissimilarities in approaches to determine resilience. This could eventually give rise to interoperability issues in the following scenarios: i) inconsistencies in research arises when comparing resilience levels between societies determined from methodologies, which stem from conceptualizations that are not cohesive and ii) conflict arises in trying to merge disparate approaches (stemming from different notions of resilience) to create a resilience application within information systems as well as operational methodologies to conduct resilience studies.

In this regard, a resilience ontology can account for these aforementioned issues as it "gives an explicit partial account" (Guarino and Giaretta, 1995) of the conceptualization of resilience. An ontology is not static and is made publicly available to encourage re-use and further development of the ontology. As new knowledge about socio-ecological systems and resilience arises, the ontology can be re-iterated to incorporate these changes and in turn the formalizations adjusted accordingly. If the parameters of the action of recovery are made explicit in the theory, the ontology can be used to infer whether a current system is truly resilient i.e. functioning in a healthy state or being maladaptive. Likewise, if the parameters of the coping strategies are modelled in the formal framework, the ontology can be applied to determine the current phase of the system, for example whether the system is choosing to adapt or resist environmental changes. Additionally, the resilience ontology provides a pattern for the creation of a knowledge-driven resilience application within a geographic information system. There is evidence that ontologies are a useful means of encoding knowledge to improve runtime of applications (see Guarino (1998)). Furthermore, it facilitates reasoning wherein rules can be inferred within the ontology and applied for e.g. in an agent based environment, to create new knowledge.

Through the organization of the resilience knowledge presented, linkages between concepts were unearthed. In the formal theory, it is indicated that the action of adapt referred to in research as adaptive capacity was specified as part of the coping strategy of a system. Thus, to adapt or the process of adaptation falls within the formal framework of resilience. Researchers have varying views regarding whether or not resilience falls under the umbrella of adaptation or vice versa. Folke et al. (2010) suggested that adaptability is a prerequisite for resilience whereas Klein et al. (2003) proposed that resilience falls under the bigger picture of adaptive capacity and adaptation. The formalization therefore gives currency to the notion that adaptation falls under the purview of resilience.

6.5 Limitations of Research

Every scientific work is subjected to limitations, which are usually imposed by conditions beyond the control of the researcher. This research did not transpire according to the author's vision. It would have been ideal if sufficient data was acquired to generate instances to test the formal theory of resilience. The following limitations were also encountered:

1. Data: Data secured for querying the formalization was not sufficient to generate the instances needed for testing in a computational environment. Furthermore, due to the time frame in which the dissertation had to be completed new data could not have been sourced to facilitate testing.

2. Formal theory:

    - Once the formal theory was completed, it was not feasible to poll domain experts regarding the quality of the resilience ontology due to time constraints.

    - This work did not explore or make explicit the specificities of the coping strategies and the action of recovery. Each strategy has its own parameters, which determine whether actions taken are in line with a system withstanding, adapting, maintaining or absorbing a disturbance. Likewise, the occurrence of recovery has its own parameters to determine whether or not a system is functioning in a healthy state after a strategy is undertaken.

3. The temporal nature of the strategies and by extension resilience were not considered in this work.

6.6 Conclusion

This chapter examined the formal theory of resilience. Firstly, the theory was assessed based on its construction. The technical assessment examined the significance, objectivity, validity and reliability of the ontology. Secondly, the theory was evaluated against two established resilience definitions put forward by the Resilience Alliance and the UN/ISDR. Based on the assessment, it was determined that the former notion had internal contradictions rendering the definition inconsistent. On the other hand, the latter definition was closely aligned to the formal theory and shared core elements of the ontology. It must be made known that the resilience ontology does not represent an exhaustive domain ontology. There is work still to be done as the coping strategies warrant further investigation in order for its processes to be formally specified. Consequently, applying the formalization in its current form to some datasets would not produce new knowledge. Nevertheless, the ontology provides a useful starting point to straighten out the conceptual blockage that occurs on the theoretical side of resilience while at the same time providing a formalization necessary for computational resilience research.

Chapter 7

Conclusion

To address the ambiguities that compound resilience, a formal theory of resilience was created. Through ontology engineering principles, the notion of resilience was modelled and a semantic reference frame for the concept was formed. This scientific work showed that an ontology is an appropriate tool, which can be used to account for conceptual fuzziness. The achievements of the research are summarized as follows:

1. **A general definition of resilience**: *The ability of a system to cope with an external factor that undermines it, with the system bouncing back.* This definition represents a decomposition of the views expressed by experts across disciplines and served as the foundation for the formal theory.

2. **The relations between key terms** in the resilience concept were specified based on DOLCE basic primitive relations. In this activity it was determined that the process of adaptation is a coping strategy of resilience. Thus adaptation falls under the purview of resilience.

3. **Content ontology design pattern for referential qualities**. The pattern was devised to overcome the shortcoming of modelling resilience under DOLCE. In DOLCE

qualities inhere in one host unlike resilience which is dependent on a host and a referent. Although the pattern arose out of the work done in resilience, it can be applied to other concepts that are also require a referent.

4. **Formalization and semantic reference frame for resilience**.

At present, the formal theory of resilience is elementary, nevertheless, it provides the ripe opportunity for further development and research.

1. The opportunity exists to draw upon the knowledge of the coping strategies and make explicit their processes within the ontology. By incorporating the parameters of the strategies, inferences can be deduced from the knowledge encoded, for example, rules pertaining to the tasks undertaken by the system to adapt to sea level rise. In this sense, the domain ontology can be extended into a task ontology. These rules could be applied over data in an agent based environment to facilitate reasoning about an agent's (system) behaviour in response to environmental variability. Agent Based Simulation is a promising research area for resilience as it allows for modelling complex system behaviour and analysis of emergent behaviour patterns. As a result, such analysis could lead to more informed methodological approaches for resilience as well as policy formation to build resilient societies.

2. In addition to expanding the coping strategies, knowledge pertaining to socio-ecological system dynamics and inter-relations should be examined and made explicit within the ontology if reasoning about system behaviour to environmental change is to occur.

3. This formal theory provides a platform for the integration of resilience and vulnerability. If vulnerability is semantically modelled in the same manner as resilience, linkages between both concepts would be made clear, which in turn would pave the way towards operational methods.

4. The opportunity also exists to evaluate the temporal aspects of the coping strategies. In

Daniel and Ortmann (2011), it was suggested that societies undergo one of the coping strategies at some point in time and that this process becomes cyclical as the external factor evolves. Investigating the temporal dimension of strategies would impact planning efforts as societies strive to attain sustainability amid climate variability.

5. In future development, domain experts should be sought to evaluate the knowledge encoded as well as the usefulness of the formalization. If this is done, the strengths and weaknesses of the ontology would be revealed and the developer can make the necessary changes to strengthen the formal theory.

In conclusion, it is the intention of the author that this formal theory will commence stronger efforts between both theoretical and practical research sides towards operationalization of resilience and integration with vulnerability assessments. The formal theory of resilience marks the initial phase in this direction and provides the foundation for further development. This work has shown that inconsistencies exist amongst conceptualizations and thus underscores that a clear meaning (semantics) of a concept is imperative to its operationalization both computationally and in methodology.

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Appendix A

Glossary of Concepts

Name	Associations	Acronym	Description	Type
External Factor	Threat; Stress; Disturbance	-	stimuli that occurs outside of the system, which undermines the system and has a damage potential attached.	Concept
System	-	-	Complex interaction of elements with these interactions specifying a particular relation between elements (von Bertalanffy, 1950).	Concept

Socio-ecological System	-	SES	Complex interaction of elements that constitute both the social and ecological systems specifying the interlinkages between both systems (adapted from (von Bertalanffy, 1950).	Concept
Ability	-	-	The capacity of the system to do something (Waite et al., 2006).	Concept
Coping Strategy	-	-	Mechanisms used to effectively manage or deal with an external factor (adapted from (Waite et al., 2006)).	Concept
Maintain	Return; Remain	-	To preserve a particular system state in face of an external factor or preserving the original state after an external factor manifests.	Concept
Withstand	Resist	-	To keep out an external factor from undermining the system, once it is perceived.	Concept

Absorb	-	-	The amount of an external factor a system can take in before a change occurs within the system.	Concept
Adapt	Self-organization	-	To adjust a system's behaviour and characteristics in order to enhance its ability to deal with an external factor unto the system and offset potential damage. These adjustments are based on experiences and lessons learnt in dealing with environmental changes (adapted from (Burton et al., 2001; Brooks, 2003)). Self-organization is a process of adapting.	Concept
Bouncing Back	Recovery	-	The function of recovery undertaken by the system from adversity (adapted from (Wildavsky, 1988).	Concept

Resilience	-	-	The ability of a system to cope with an external factor that undermines it with the system bouncing back.	Concept
Socio-ecological system name	-	-	Name of socio-ecological system	Instance Attribute
Is-A	-	-	Is-A describes a hierarchical relationship between a superclass entity and a subclass entity.	Relation
Quality	-	-	“Qualities are entities that can be perceived or measured” (Masolo et al., 2003).	Relation
Temporal-part	-	-	Parthood relationship for entities that does not change in time (Masolo et al., 2003)	Relation
Specific-constant-dependence	-	-	“A particular x is specifically constantly dependent on a particular y iff at any time t, x cannot be present at t unless y is present at t” (Masolo et al., 2003).	Relation

Appendix B

Resilience Ontology in OWL-DL

```
Prefix: cp: <http://www.ontologydesignpatterns.org/schemas/cpannotationschema.owl#>
Prefix: dns: <http://www.loa-cnr.it/ontologies/ExtendedDnS.owl#>
Prefix: temp: <http://www.loa-cnr.it/ontologies/TemporalRelations.owl#>
Prefix: xml: <http://www.w3.org/XML/1998/namespace>
Prefix: rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
Prefix: ro: <http://www.jensortmann.de/ontologies/resilience-ontology1.owl#>
Prefix: rq: <http://www.jensortmann.de/ontologies/referential-quality1.owl#>
Prefix: xsd: <http://www.w3.org/2001/XMLSchema#>
Prefix: owl: <http://www.w3.org/2002/07/owl#>
Prefix: dol: <http://www.loa-cnr.it/ontologies/DOLCE-Lite.owl#>
Prefix: space: <http://www.loa-cnr.it/ontologies/SpatialRelations.owl#>
Prefix: dc: <http://purl.org/dc/elements/1.1/>
Prefix: rdfs: <http://www.w3.org/2000/01/rdf-schema#>

Ontology: <http://www.jensortmann.de/ontologies/resilience-ontology1.owl>
Import: <http://www.jensortmann.de/ontologies/referential-quality1.owl>
AnnotationProperty: rdfs:comment
```

```
Datatype: rdf:PlainLiteral

ObjectProperty: dol:has-quale

ObjectProperty: dol:inherent-in

ObjectProperty: dol:specific-constant-dependent

ObjectProperty: dol:part-of

ObjectProperty: dol:part

ObjectProperty: dol:specifically-constantly-dependent-on

Class: ro:resilience

    Annotations:
        rdfs:comment "The ability of a system to cope with an
        external factor with the system bouncing back"

    SubClassOf:
        dol:has-quale some dol:quale,
        rq:referential-quality,
        dol:specifically-constantly-dependent-on some ro:damage_potential,
        dol:inherent-in only ro:system

Class: ro:withstand
```

```
    Annotations:
        rdfs:comment "To keep out an external factor from undermining the system."

    SubClassOf:
        dol:part-of some ro:coping_strategy,
        dol:process

    DisjointWith:
        ro:maintain, ro:absorb, ro:adapt

Class: dol:quale

Class: ro:ability

   SubClassOf:
        dol:has-quale some dol:quale,
        rq:referential-quality,
        dol:inherent-in only ro:system,
        dol:specifically-constantly-dependent-on some ro:coping_strategy


Class: rq:referential-quality

Class: ro:adapt

    Annotations:
        rdfs:comment "Continuous change by a system in face of a
        disturbance. The system adjusts accordingly due to its experience."
```

```
    SubClassOf:
        dol:part-of some ro:coping_strategy,
        dol:process

    DisjointWith:
        ro:withstand, ro:maintain, ro:absorb


Class: dol:quality

Class: ro:bouncing_back

    Annotations:
        rdfs:comment "The function of recovery undertaken by a system
        from adversity."

    SubClassOf:
        dol:achievement,
        dol:specific-constant-dependent some ro:resilience

Class: ro:external_factor

    Annotations:
        rdfs:comment "Factor outside of the system that undermines
        the system."

    SubClassOf:
        dol:specific-constant-dependent some ro:resilience,
        dol:quality
```

```
Class: dol:achievement


Class: dol:arbitrary-sum


Class: ro:maintain

    Annotations:
        rdfs:comment "To preserve a particular system state in face of
        a disturbance."

    SubClassOf:
        dol:part-of some ro:coping_strategy,
        dol:process

    DisjointWith:
        ro:withstand, ro:absorb, ro:adapt

Class: ro:absorb

    Annotations:
        rdfs:comment "The amount of disturbance a system can take in
        before a change occurs within the system."

    SubClassOf:
        dol:part-of some ro:coping_strategy,
```

```
        dol:process

    DisjointWith:
        ro:withstand, ro:maintain, ro:adapt

Class: ro:system

    Annotations:
        rdfs:comment "Complex interaction of elements with these interactions
        specifying a particular relation between elements (von Bertalanffy 1950). "

    SubClassOf:
        dol:arbitrary-sum
         and (dol:specific-constant-dependent some ro:resilience)


Class: ro:socio-ecological_system

    Annotations:
        rdfs:comment "Complex interaction of elements that constitute the
        social and ecological systems together with their relations
        (adapted from von Bertalanffy 1950)."

    SubClassOf:
        ro:system

Class: ro:damage_potential

    Annotations:
```

```
        rdfs:comment "A potential for an event to occurr that causes damage.
        For example the potential for a flood to come, for an earthquake to
        strike, or for hurricane to form."

    SubClassOf:
        ro:external_factor,
        dol:specific-constant-dependent some ro:resilience

Class: ro:coping_strategy

  Annotations:  rdfs:comment "The ability to effectively manage or deal with
  an external factor via some mechanism (adapted from Oxford Dictionary 2006)."

    SubClassOf:
        dol:specific-constant-dependent some ro:resilience,
        (dol:part some ro:absorb)
         and (dol:part some ro:adapt)
         and (dol:part some ro:maintain)
         and (dol:part some ro:withstand),
        dol:process

Class: dol:process

Individual: ro:trinidadian_society

    Types:
        ro:socio-ecological_system

    Facts:
```

```
     dol:specific-constant-dependent  ro:trinidadian_society_resilience_to_sea_level_rise

Individual: ro:trinidadian_society_ability

    Types:
        ro:ability

    Facts:
     dol:inherent-in  ro:trinidadian_society,
     dol:specifically-constantly-dependent-on  ro:trinidadian_society_coping_strategy


Individual: ro:sea_level_rise_damage_potential

    Types:
        ro:damage_potential

    Facts:
     dol:inherent-in  ro:trinidadian_society,
     dol:specific-constant-dependent  ro:trinidadian_society_resilience_to_sea_level_rise


Individual: ro:trinidadian_society_coping_strategy

    Types:
        ro:coping_strategy

    Facts:
     dol:specific-constant-dependent  ro:trinidadian_society_resilience_to_sea_level_rise
```

```
Individual: ro:trinidadian_society_resilience_to_sea_level_rise

    Types:

        ro:resilience

    Facts:

     dol:specifically-constantly-dependent-on  ro:sea_level_rise_damage_potential,

     dol:inherent-in  ro:trinidadian_society


Individual: ro:trinidadian_society_recovery

    Types:

        ro:bouncing_back

    Facts:

     dol:specific-constant-dependent  ro:trinidadian_society_resilience_to_sea_level_rise
```

Independent Study Declaration

This thesis entitled "Formal Theory of Resilience" is my independent research undertaken over the past six months as part of the fulfilment of the Masters of Science degree in Geoinformatics and is written by myself. The dissertation is written by myself and has not been submitted to any other educational institute to obtain other qualifications. Wherever the work of other people are used in the thesis, the authors are fully cited.

Desiree Daniel,

Münster, 27.12.11