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CONCEPTUAL DESIGN OF AN AGENT-BASED MODEL TO SIMULATE RESILIENCE OF NORTHERN ALASKAN COMMUNITIES

A Thesis in

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by

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ABSTRACT

Climate change is accelerating the rate at which permafrost (frozen ground) is thawing in the Arctic. In turn, this has complex and interdependent impacts on the food, energy, and water security (FEWS) of Arctic communities. Relocating communities has cost millions of dollars, and communities which cannot afford to move must adapt. Resilience-building research currently does not view northern Alaskan communities holistically, nor does it account for cascading effects of permafrost thaw or the relationship between people and infrastructure. This conceptual design of a human-centered agent-based model accounts for these relationships and serves as a relevant and insightful tool for government and community decision-makers to use when forecasting permafrost impacts on community resilience. User interviews were conducted to understand the needs of government decision-makers, partially informing a problem space also defined by North Slope Borough census information and recent community permafrost thaw impact survey data. Ultimately, agent-based model dynamics and associated design choices are discussed, supported by strategies for translation to a computational model.

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Chapter 1

Introduction

1.1 Motivation

1.1.1 Climate Change and Arctic Socio-Ecological Systems

NASA defines climate as the usual weather of a place, while the Earth's climate is the combination of all climates around the world together (May, 2017). Climate change is a change in the usual weather found in a place but is also considered the change in Earth's climate which takes hundreds or even millions of years (May, 2017). Earth's climate is always changing, and people who study Earth see that its climate is getting warmer (May, 2017). Small changes in Earth's temperature can have large effects, such as snow and ice melt, which is already happening around the world (May, 2017). Scientists think that Earth's temperature will keep going up for the next 100 years (May, 2017).

A socio-ecological system, according to Alessa & Kliskey (2021, p. 165), is "characterized by feedbacks, which occur between human values, perceptions, and behaviors and the biophysical components of the ecosystems in which people exist resulting in a resilient or vulnerable trajectory leading to sustainability or collapse." Both the social and ecological components of these systems are interrelated, as is represented in Figure 1.1. The social component refers to all human activities that include economy, technology, politics, and culture, while the ecological component refers to the biosphere (South American Institute for Resilience and Sustainability Studies, 2022). In Arctic societies, social and ecological components are particularly interrelated, where changes in either component are very likely to impact the other. As we observe drastic changes to Arctic environments, such as snow and ice melt, human communities in the Arctic will also drastically change. One of the greatest challenges in Arctic communities which impacts all life in these regions is permafrost thaw.

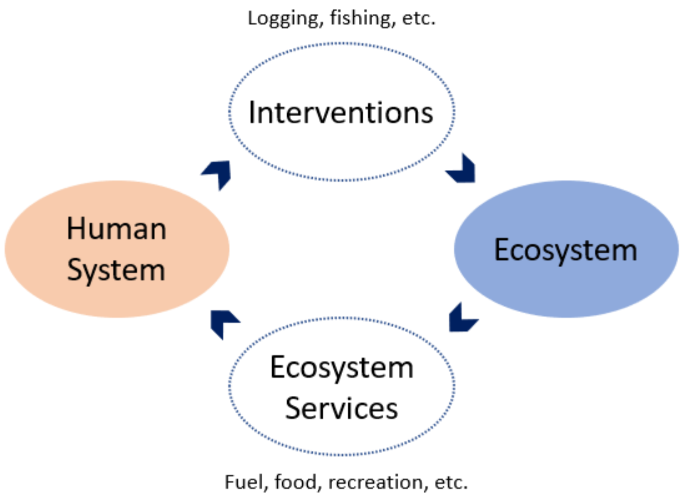

Figure 1.1. Socio-ecological system relationships[1]

1.1.2 Permafrost Thaw and Arctic Socio-Ecological Systems

Permafrost refers to land (soil, sand, rock, and ice) which has remained below 0 degrees Celsius for two or more consecutive years (Biskaborn, 2020). Mostly found within polar regions and high mountain ranges, permafrost underlies nearly a quarter of the northern hemisphere, extending up to 1.7 kilometers into the Earth. Permafrost can be up to 70 percent ice, the thawing of which results in damage to the built environment and, ultimately, the lives of people who are part of Arctic communities (Biskaborn, 2020). On a global scale, the thawing of permafrost complicates our ability to forecast climate change dynamics as organic materials preserved within it are broken down by bacteria, a process which releases carbon dioxide and methane into the

[1] Reproduced from the SARAS Institute (South American Institute for Resilience and Sustainability Studies, 2022)

atmosphere and accelerates global warming (Biskaborn, 2020). The impacts range from affecting local livelihoods and lifestyles to the ability to maintain and deploy national defense assets. Such a complex system necessitates a more strategic approach if we are to make evidence-based decisions with respect to economies, infrastructure, food, energy and water security (FEWS), national response assets (e.g., search and rescue, law enforcement, border protection, humanitarian response and community health and vitality), taxpayer burdens of relocating remote communities whose sustainability is threatened by climate change and other variables, all of which are interdependent on social and behavioral actions at multiple scales (Office of the Under Secretary of Defense for Policy, 2019; Street, 2020). By 2050, approximately 3.6 million Arctic inhabitants will be affected by damage to infrastructure caused by permafrost thaw. In total, nearly 70 percent of the infrastructure in the Arctic will be impacted (Hjort et al., 2018). In addition, approximately $15.3 trillion in civil infrastructure assets will require assessment to ensure that panarctic interests can still be served (Suter et al., 2019).

The impacts of permafrost thaw on community infrastructure are so extensive that more and more Alaskan communities (such as Shishmaref, Newtok, Kivalina, etc.) vote to relocate or will have no choice but to relocate (Xiyue Li, 2020). However, relocation comes with great costs related to coordination and resources (Xiyue Li, 2020). For instance, the cost to resettle Alaskan village Shishmaref has been estimated at $180 million (Waite, 2019). It remains unclear where the funding will be derived from to support these relocation efforts and supplies, especially when there is no dedicated funding stream, lead agency, or policy framework to guide Alaskan communities in need of relocation (Xiyue Li, 2020). Relocation has also occurred in other countries, when necessary, in response to natural hazard risk (Bromwich, 2016), but relocation is certainly not a simple solution for communities/villages to opt for as permafrost thaw continues or accelerates.

1.2 Design Intention

Resilience-building research currently does not view northern Alaskan communities holistically, nor does it account for cascading effects of permafrost thaw or the relationship between people and infrastructure. Not accounting for how permafrost impacts cascade throughout communities in a holistic sense implicates isolated solution design that cannot tolerate the complexity of the socio-ecological system. As well, without account for relationships between people and infrastructure, it is not possible to prioritize which infrastructure are most critical to sustain communities. Agent-based modeling (ABM) presents an opportunity to support decision-makers in adapting a more holistic approach.

This work follows the design thinking process to conduct the conceptual design of an agent-based model of the Arctic socio-ecological system. First discussed is a detailed overview of community stakeholders and the socio-ecological systems they are a part of. Then, insights from interviews with two community stakeholders, who are also subject experts, are summarized. The knowledge from both the detailed overview and the interviews is leveraged to expose model user needs and define the most critical problems to address. Ultimately, user needs guide, and are met through, the design of this conceptual ABM.

The remainder of the thesis is organized as follows. Chapter 2 provides an overview of North Slope Borough communities with respect to demographics, environmental change, and impacted infrastructure. Chapter 2 also reviews the case of using ABM to study the Arctic and to study resilience. Chapter 3 discusses best practices for ABM in engineering design, and how this thesis aligns with both the design process and the systems modeling process. Chapter 4 discusses the conceptual ABM design process. This includes details of how this work leverages user needs and insights from North Slope Borough community data to define the problem space, and includes an explanation of model dynamics, design decision-making, and translation to computational model. A summary of this work, its limitations, and opportunities for future work are discussed in

Chapter 5. In Chapter 6, the Epilogue, I discuss my journey through academia, and how the work I’ve completed throughout this master’s thesis has influenced my decision to earn a Ph.D. in Systems Engineering.

Chapter 2[2]

Background

2.1 Communities of Interest

The information discussed in this chapter regarding the people, environment, and infrastructure of the North Slope Borough has been gathered via recent community surveys conducted in the region by both representatives of the North Slope Borough as well as a team of scientists. The results of the first survey, which is a census conducted by the North Slope Borough, are discussed in Section 2.1.2 (North Slope Borough, 2019). In section 2.1.4., the results of the second survey conducted by Liew et al. (2022) describe environmental impact on community infrastructure. When modeling systems that already exist, it is important gain knowledge of that system's characterization. Similarly, from a user-centered design perspective, it is important to understand stakeholders well at the beginning stages of the design thinking process. The purpose of including information from these two surveys in this chapter is to provide a background of important information regarding the North Slope Borough which informs the insights discussed in the "Empathizing with the User" and "Defining the Problem Space" sections of Chapter 4.

2.1.1 NSF NNA and PIPER

This research is conducted in contribution to the National Science Foundation's (NSF) Navigating the New Arctic (NNA) program. The NNA tackles convergent scientific challenges in the rapidly changing Arctic, that are needed to inform the economy, security and resilience of the nation, the larger region, and the globe (National Science Foundation a, n.d.)

[2] This chapter is based on work that was published in The Arctic Institute (Hicks et al., 2021)

NNA PIPER (People Infrastructure Permafrost Resilience) is a team of engineers, geoscientists, and social scientists who collectively study resilience and adaptation to the effects of permafrost degradation. The goal of this NSF NNA project is to understand the complex interrelationships and mutual impacts of continued climate change in the Arctic among the following components: permafrost degradation and coastal erosion, civil infrastructure and development, and community well-being and socio-demographic and cultural resilience (People Infrastructure Permafrost Resilience, 2020). The output of this five-year collaboration, in which we are currently in the third year, are tools for communities which help them make decisions about adaptation. This thesis and the work it details will contribute to this set of tools intended to aid communities in response to the effects of permafrost thaw.

2.1.2 North Slope Borough Demographics

Point Lay, Wainwright, Utqiaġvik, and Kaktovik (see Figure 1.2 below) are four communities of the North Slope Borough, Alaska in partnership with which NNA PIPER has focused its scientific inquiry.

Figure 2.2. Alaskan communities Point Lay, Wainwright, Utqiaġvik, and Kaktovik

The United States Census Bureau's report (United States Census Bureau, 2021) contains demographic data for the North Slope Borough, but it differs from the census the North Slope Borough conducts on its own via their Economic Profile & Census Report (North Slope Borough, 2019). This work will focus solely on the demographic information from the 2019 North Slope Borough Economic Profile & Census Report (North Slope Borough, 2019), since it includes details of population, income, housing, subsistence, health, and food insecurity which are most relevant to subjects discussed as a part of this thesis. The details within this section regarding the people of the North Slope Borough inform the insights discussed in the "Empathizing with the User" and "Defining the Problem Space" sections of Chapter 4. All information in section 2.1.2, including Tables 2.1-2.4, is derived from the 2019 North Slope Borough Economic Profile & Census Report (North Slope Borough, 2019) unless specified otherwise.

Table 2.1. Demographic population data for the North Slope Borough and villages communities[3]

	North Slope Borough Community	**Villages Community**
Total Population	8638	2955
Median Age of Total Population	26	25
Percent Iñupiat	84%	92.72%
Percent Caucasian	7.6%	5.22%
Percent Other	8.40%	2.51%

[3] Reproduced from the 2019 North Slope Borough Economic Profile & Census Report (North Slope Borough, 2019)

Table 2.1 provides an overview of demographic population data for the North Slope Borough community and villages community, which are populated by 8638 people and 2955 people, respectively. However, Kaktovik, Point Lay, Utqiaġvik, and Wainwright (the North Slope Borough communities of focus for this thesis) are populated by a total of 5366 people in total (Liew et al., 2022). The demographic information in Table 2.1 also makes clear that Iñupiat people are the primary population in North Slope Borough communities and village communities. According to the North Slope Borough Economic Profile & Census Report, Iñupiat households continue to increase as a percentage of the total population in all communities (North Slope Borough, 2019).

The North Slope Borough Economic Profile & Census Report also states age and youth dependency ratios are both increasing (North Slope Borough, 2019). Borough-wide, the senior population is nearly the same percentage of the population as it was in 2015; at the village level, the senior population is growing the most in Kaktovik, Point Hope, Point Lay, and Utqiaġvik (North Slope Borough, 2019).

Table 2.2. Demographic income data for the North Slope Borough and villages communities[4]

	North Slope Borough Community	**Villages Community**
Number and Percent of Labor Force Unemployed	667 (32.2%)	508 (48.5%)
Average Iñupiat Household Income	$67,389	No data

[4] Reproduced from the 2019 North Slope Borough Economic Profile & Census Report (North Slope Borough, 2019)

Table 2.2 provides an overview of demographic income data for the North Slope Borough community and villages community, showing that the amount of the labor force unemployed in both communities is high, but is higher in the villages community. Iñupiat households have about 72% of the total average household income of Caucasian households and about 95% of the total income of "other" ethnic households (North Slope Borough, 2019). Using federal poverty guidelines, 27% of Iñupiat households in the North Slope Borough can be considered, in an economic sense, living in poverty (North Slope Borough, 2019). As shown in Table 2.2., average Iñupiat household income is $67,389, but according to the North Slope Borough Economic Profile & Census Report, income has almost no impact of an Iñupiat household's dependence on subsistence foods (North Slope Borough, 2019). The four communities with the highest proportions of low-income households – Atqasuk, Nuiqsut, Point Lay, and Wainwright, have most households with a very high (>50%) dependence on subsistence foods (North Slope Borough, 2019).

Table 2.3. Demographic housing data for the North Slope Borough and villages communities[5]

	North Slope Borough Community	**Villages Community**
Total Number of Dwelling Units	2496	937
Number of Vacant Units and Vacancy Rate	231 (9.25%)	153 (16.33%)
Total Number of Occupied Households	2265	774
Average Number of People Per Household	3.7	3.89

[5] Reproduced from the 2019 North Slope Borough Economic Profile & Census Report (North Slope Borough, 2019)

In recent years, the availability, condition, and cost of housing across the North Slope has become a primary concern of residents. Significant issues facing Borough residents include overcrowding, housing needs, and utility costs (North Slope Borough, 2019).

As Table 2.3 shows, the total number of dwelling units in the North Slope Borough community and villages community is 2496 and 937, respectively. Almost 73% of the housing stock across both communities is comprised of single-family homes (North Slope Borough, 2019). For the communities outside of Utqiaġvik, single-family homes account for over 90% of the available housing inventory (North Slope Borough, 2019). Duplex units, on average, are the most expensive for renters and owners, while multifamily units that have three or more units are the lowest cost to the occupant (North Slope Borough, 2019). On average, Caucasian households pay roughly $100/month more than Iñupiat households for rent and $400/month more for a mortgage (North Slope Borough, 2019). In total, 86% of the housing stock across the North Slope is over 20 years old while only 7% is less than 10 years old (North Slope Borough, 2019). According to Table 2.3, most of the total number of dwelling units are considered occupied households, however, there is a 9%-17% vacancy rate depending on discussion of the North Slope Borough community or the villages community.

There is a significant difference in the mean residents per household when the North Slope Borough Economic Profile & Census Report data is divided by household ethnicity (North Slope Borough, 2019). Most of the population lives in Utqiaġvik, as does the majority of the non-Iñupiat ethnicities (North Slope Borough, 2019). As Table 2.3 shows, the average number of people per household (PPH) for North Slope Borough community and villages communities is 3.7 and 3.89, respectively. Iñupiat households have an average of 4.01 PPH compared to Caucasian households, at an average of 2.17 PPH (North Slope Borough, 2019). The North Slope Borough Economic Profile & Census Report states family size has nearly doubled across the North Slope Borough, and overcrowding effects Iñupiat households more than others (North Slope Borough, 2019). Based on the rooms per person method of determining overcrowding, 32% of residents live in overcrowded housing units across the North Slope, while over 22% of all residents live in “very overcrowded” housing units (North Slope Borough, 2019). Non-Iñupiat households account for less than 20% of total housing units on the North Slope, and overcrowded housing units among non-Iñupiat’s is very low or nonexistent in most villages (North Slope Borough, 2019). Given the extent of overcrowding in all North Slope communities, the construction of new housing and renovation of dilapidated housing is needed (North Slope Borough, 2019). Extending road and power infrastructure to platted residential lots is one way to allow for additional housing construction (North Slope Borough, 2019).

The North Slope Borough Economic Profile & Census Report also states that, borough-wide, the survey data suggests the primary source of heat for housing units is diesel oil (51%) with natural gas second at 45%, and that running water is available in over 90 percent of housing units (North Slope Borough, 2019).

Table 2.4. Demographic subsistence data for the North Slope Borough and villages communities[6]

	North Slope Borough Community	**Villages Community**
Percent of Iñupiat Households Using Subsistence Foods	96.20%	96.20%
Percent of Households Receiving Half or More of Diet from Subsistence Foods	58.30%	71.50%

[6] Reproduced from the 2019 North Slope Borough Economic Profile & Census Report (North Slope Borough, 2019)

Subsistence is an important part of cultural life for many on the North Slope. As shown in Table 2.4, 96.20% of Iñupiat household in the North Slope Borough community and villages community reported using subsistence foods. However, increasing income is associated (sparingly) with decreasing amounts of subsistence consumption in the diets of Iñupiat households (North Slope Borough, 2019).

Increasing income isn't the only factor in decreasing subsistence. Nearly a third of household heads have decreased their participation in gathering plants and berries Nearly a third of household heads have decreased their participation in gathering plants and berries (North Slope Borough, 2019). One community had a substantial "decreased a lot" response when asked about whaling activities, while in Utqiaġvik, nearly a quarter of the whaling crews experienced a dramatic decrease in whaling activities (North Slope Borough, 2019). Point Lay also stands out because a majority of its whaling crews (52%) report some level of decrease in whaling activities (North Slope Borough, 2019). The harvesting of seals or walrus experienced even greater decreases compared to whaling activities over the last five years; four out of ten marine mammal hunters report a decrease in harvesting activities (North Slope Borough, 2019). Atqasuk, Utqiaġvik, and Point Lay have reported about a 50% decrease in sea mammal hunting, but decreases in the hunting of land mammals, primarily caribou, mirror decreases in sea mammal hunting (North Slope Borough, 2019). One community, Point Lay, had dramatic declines in their proportion of Iñupiat households attempting to harvest ringed and bearded seals, which has been attributed to changes in shore-fast ice (North Slope Borough, 2019).

The percent of householders receiving half or more of their diet from subsistence foods, according to Table 2.4, is 58.30% and 71.50% for the North Slope Borough community and villages community, respectively. However, Anaktuvuk Pass, Atqasuk, Point Hope, and Point Lay experienced decreases in in average subsistence expenditures between 2015 and 2019 (North Slope Borough, 2019).

Those individuals who are assessed in “poor and fair” health, which is in less than good health, are approximately 12% of the Iñupiat population (North Slope Borough, 2019). Iñupiat individuals in Utqiaġvik easily have the highest assessment of “excellent” health, while the communities of Anaktuvuk Pass, Point Hope and Point Lay have half the Iñupiat individuals in very good or excellent health (North Slope Borough, 2019). 30.1% of household heads with incomes below the poverty level rate their health as poor/fair, whereas in contrast, only 16% of Iñupiat household heads with incomes above the poverty level have the same self-assessment (North Slope Borough, 2019).

There are many issues related to food insecurity in the North Slope Borough, including a lack of income to purchase food, the high cost of food, food insecurity as it relates to lack of employment, the unpredictability of income (specifically dividend income), and the lack of stores with sufficient stocks of food (North Slope Borough, 2019). Approximately 36% of Iñupiat households have some form of food insecurity – about three times the national average, while worry about not having any food to eat was consistent across all subsistence dependencies (North Slope Borough, 2019). Households most dependent on store bought foods are those most worried about obtaining all the subsistence foods they need (North Slope Borough, 2019). With the exception of Point Hope and Wainwright, the remaining six communities have seven (at least) out of ten households who have declared the difficulties they face in obtaining healthy foods are due to their inability to obtain them from their local store (North Slope Borough, 2019). Two communities, Anaktuvuk Pass and Wainwright, stand out as a third of their household heads said there were times they did not have enough to eat (North Slope Borough, 2019). Point Lay had about a quarter of their household heads respond about their lack of food, making Anaktuvuk, Wainwright, and Point Lay three communities that have five to seven times the national measure of 4.9% of household heads reporting a lack of food (North Slope Borough, 2019). The remaining five of the other NSB communities had proportions of 20% or less but are still three to four times the national proportion

(North Slope Borough, 2019). About half of all households who could not afford to purchase enough food were not working, but unemployment seemed to be critically important in Utqiaġvik where 70% of the households unable to purchase food were not working (North Slope Borough, 2019). Nearly every household in Atqasuk, Utqiaġvik, Point Lay, and Wainwright cited the high cost of foods and the high costs of other bills as the main reason they could not afford to purchase enough food (North Slope Borough, 2019). On the critical measure of not having enough to eat ("very low food security") young and elderly males and middle-aged women were most at risk although these are small to moderate differences (North Slope Borough, 2019). Almost all Iñupiat households (70%-80%) of either gender at any age seem to have reasonable access to obtaining the amount of traditional foods they need, although middle-aged male households have slightly more difficulty in obtaining subsistence foods (North Slope Borough, 2019).

2.1.3 North Slope Borough Infrastructure Composition

The North Slope Borough consists of various types of infrastructure. However, this thesis focuses on that which supports resident access to food, energy, and water. Some infrastructure within the North Slope Borough is of greater importance to resident communities given the resources it provides and is also associated with various levels of criticality to defend from the effects of permafrost thaw. There is various infrastructure which the conceptual model central to this thesis is designed to account for, and they are considered relevant only if they pertain to food, energy, or water resources. Regarding food, housing is of course critical to consider as it is key for food storage and food preparation for safe eating. As well, grocery stores or convenience marts are examples of shared infrastructure that provide food resources. While trends seem to be shifting, community members of the North Slope Borough also hunt and fish for much of their food, making infrastructure such as snow mobiles essential for reaching grounds for these activities and hauling back loads. Water is a resource that is normally an input to the home and other structures humans are intended to inhabit (such as schools) but can also be found bottled at grocery stores and convenience marts. Often, water requires a treatment to be consumed safely, and so important infrastructure relevant to water access is water sanitation facilities. Energy can be thought of as the materials, such as fuels, which help satisfy needs such as powering technology and heating of people's homes. When we think of energy and its relationship to infrastructure, we consider any infrastructure which delivers fuels or energy sources to communities. This can be infrastructure such as barges, local storage facilities, lumbar harvesting tools, etc.

2.1.4 Permafrost Thaw Impacts in the North Slope Borough

The following information is from a community survey conducted by Liew et al. (2022). The survey discussed in this section is separate from the North Slope Borough Economic Profile and Census Report (North Slope Borough, 2019) which was discussed in section 2.1.2. The details within this section regarding environmental impacts on infrastructure inform the insights discussed in the "Empathizing with the User" and "Defining the Problem-Space" sections of Chapter 4.

Point Lay, Wainwright, Utqiaġvik, and Kaktovik are the four coastal communities from which observations by residents were collected via a recent community survey (Liew et al., 2022). All four of these communities are underlain by continuous ice-rich permafrost with varying degrees of degradation and coastal erosion (Liew et al., 2022). Based on reports from survey participants, surface water ponding, ground surface collapse, and differential ground settlement are the three types of changes in ground surface manifested by permafrost degradation that are most frequently reported by participants (Liew et al., 2022). Houses are reported as the most affected type of infrastructure in the Arctic coastal communities, while wall cracking and house tilting are the most reported types of residential building damage (Liew et al., 2022). The authors also note that effects of permafrost degradation and coastal erosion on civil infrastructure vary between communities (Liew et al., 2022). However, the types of damage to residential buildings reported by at least 10%

of survey respondents in total across Kaktovik, Point Lay, Utqiaġvik, and Wainwright are as follows (Liew et al., 2022):

- Surrounding water accumulation (10%)
- Doors that could not close (11%)
- Tilting of houses (13%)
- Cracking of walls (15%)

66% of the participants reported that they have seen damages to residential buildings, but only 31% of them have seen repair to the damages (Liew et al., 2022). 41% of the participants reported that they have seen damages to roads, while 26% of them have seen damages to buried pipelines and utilidors (Liew et al., 2022). There are more reported cases of damage to roads than to buried pipelines and utilidors (Liew et al., 2022). A summary of the most reported types of civil infrastructure affected by permafrost thaw, according to town, is shown in table 1.5 below.

Table 2.5. Most Reported Types of Civil Infrastructure Affected by Permafrost Thaw[7]

Towns	Most Reported Types of Civil Infrastructure Affected by Permafrost Thaw
Kaktovik	Houses (31%)
Point Lay	Runways (26%)
Utqiaġvik	Houses (28%)
Wainwright	Water and Sewer Lines (36%)
All	Houses (27%)

2.2 ABM in the Arctic

ABM has many attributes which lend it as a helpful tool for Arctic research of socio-ecological systems. ABM is a tool suitable for decision-makers facing the complex and interdependent effects of climate change. The following sections detail properties of ABM that characterize it as a premier method of forecasting permafrost impacts as part of this thesis research.

2.2.1 ABM to Simulate Complex Human Systems

A relatively new methodology used to study complex human systems, ABM is a critical tool to advance not only our understanding of the effect of permafrost thaw on a range of stakeholders, but also as a tool for co-producing potential future scenarios. An ABM utilizes autonomous agents, including humans, in a biophysical and built ecosystem (the environment) and models that behaviors of such agents who act on and change their environment, over time, to realize

[7] Adapted from the Journal of Marine Science and Engineering (Liew et al., 2022)

stated needs, goals and values (Graesser & Franklin, 1996). Agents are reactive, autonomous, goal-oriented, and continuous. It is important to note that all software agents are programs, but not all programs are agents. These software agents are often constructed in such a way that they represent real-world things, ranging from the simpler (e.g., bacteria) to the most complex (i.e., humans) (Graesser & Franklin, 1996). The construction of human agents in ABM has evolved greatly through the combined work of a global commons of practice, ranging from present-day tribal communities in Africa to urban resource use in mega-cities (Office of the Under Secretary of Defense for Policy, 2019). Agents and their environments can be used to effectively simulate real-world systems because they rely on rules that are built by diverse stakeholders. ABM is generative, and therefore can be used to generate scenarios under different environmental, decision-making, and social conditions. These characteristics are of great value to understanding the interplay of rapidly changing permafrost, and its effects, across Arctic regions at local to pan-arctic scales. With a high ceiling for complexity, ABM simulations can provide valuable insights, often revealing the "unknown unknowns" by running multiple scenarios in parallel. Such a tool can help guide which data are needed and ensure that scenarios, futures, and the implications relevant to policymaking are truly co-developed by the stakeholders most affected, such as local Indigenous communities.

2.2.2 ABM to Simulate Arctic Socio-Ecological Systems

The use of ABMs in Arctic research is not new. For instance, ABM has contributed to an integrated assessment of community sustainability by simulating how people interact with each other and adapt to changing economic and environmental conditions (Berman et al., 2004). Permafrost thaw as a hazard affecting human societies has also been studied using the MASON Northlands computational simulation model (Rogers et al., 2015). Other applications of ABM in the Arctic have included marine transport systems (Tarovik et al., 2017), animal-environmental interactions (Lesins & Higuchi, 2010), marine oil spills (Ye et al., 2019), the study of endangered species (Brilliantova et al., 2018), and migratory processes (Bystrov et al., 2019). In addition, ABM has been used to study human-environmental systems all over the globe, integral in better understanding climate change adaptations in Mongolia (Wang et al., 2013), Thailand (Entwisle et al., 2016), Germany (Troost & Berger, 2014), Qatar (Namany et al., 2020), and many other countries (Natalini et al., 2019). ABM is the focus of the Computational Modeling in Social and Ecological Sciences (CoMSES) network (Office of the Under Secretary of Defense for Policy, 2019). This network includes both researchers and users and includes stakeholders ranging from Tribes and Indigenous groups to medical professionals to engineers. Studies of environment-migration linkages are particularly common since ABM can be used to model the individual decisions of human actors (Thober et al., 2018; An, 2012). Similarly, ABM can be used to forecast environmental conditions leading to human conflict, such as between the pastoral nomads and sedentary peasants of Sudan (Kuznar & Sedlmeyer, 2005). ABM has been used to study the impacts of infrastructure damage following extreme weather events in Mississippi (Eid & El adaway, 2017) and Texas (Esmalian et al., 2019). Other ABMs have been used to explore various aspects of human-environment interactions, including foraging and its impact on hunter-gatherer settlement patterns (Sikk & Caruso, 2020), mosquito disease transmission in the Caribbean (Jindal & Rao, 2017), and the relationship between monsoon precipitation patterns and hunter-gatherer population dynamics in India (Balbo et al., 2014).

2.2.3 ABM to Simulate Permafrost Thaw Effects

ABM has also been used to study many of the effects associated with permafrost thaw, making it an appropriate tool to model their collective impact in the Arctic. As an example, ABMs have been used to guide rural infrastructure policies in response to accelerating earth destabilization in Austria (Schlögl et al., 2019). Food, energy, and water security, not just for local communities, but for the Nation as whole continues to be a growing concern as permafrost thaw induces changes which directly impact FEWS. For example, communities like the Jean Marie River First Nation, located in the Canadian Northwest Territories, have been forced to adopt actions that erode both cultural identity and sustainability (Alessa et al., 2008). ABMs have been used to assess community food security in Malawi (Dobbie et al., 2018) and explore the use of soil conservation methods in Vietnam as erosion accelerates (Quang et al., 2014). Indigenous peoples, such as those living in Guyana, often interact with their natural environment through hunting and subsistence practices, which has also been studied using ABM (Iwamura et al., 2014). Hunting is dependent upon populations of wildlife in the vicinity of communities at some range, which would be impacted greatly if animal migrations were to displace this food source. Animal migration, a complex spatiotemporal phenomenon, has been studied across landscapes using ABM due to its individual-based approach which enables exploration of the underlying processes that drive animal behavior (Tang & Bennett, 2010). Indigenous communities have been a part of many studies involving ABM to assess human-natural systems. Socio-environmental sustainability of Indigenous lands has been studied, which highlights the value of simulation models as social-ecological experiments that can synthesize interdisciplinary knowledge bases and support policy development (Iwamura et al., 2016). Other effects of permafrost thaw which have been studied using ABM include but are not limited to: Climate change (Patt & Siebenhüner, 2005), land-use change (Mena et al., 2011), human relocation (Hassani-Mahmooei & Parris, 2012), disease transmission (Tuite et al., 2017), and population density (Kocabas & Dragicevic, 2013).

2.2.4 The Case for Increased Use of ABM to Study the Changing Arctic

Agent-Based Modeling is a qualitative process that yields quantitative results; it is a computable result of an insight driven process that users to look at many outcomes and gain insights rapidly. Simulation is key when studies can’t be run due to ethical concerns. For example, this

NNA PIPER ABM simulates basic resources (food, energy, water) being cut off from communities, a situation which could not justifiably be created with actual humans – but makes for a good model.

The utilization of advanced ABM methods will significantly help to refine which types of traditional fieldwork and data are needed. It may also help to precisely guide strategic decision-making by diversifying stakeholder inputs, generating plausible scenarios and allowing the consequences and trade-offs of policy interventions to be forecast. In this way, ABM and field work may become synergistically linked. Such a hybrid approach creates less risk for local communities, fewer costs to researchers, and overall less burden to local Arctic residents. We argue that such an approach is no longer notional but necessary in the midst, and wake, of the COVID-19 pandemic. With a warming Arctic and permafrost thaw, exposure to long-frozen pathogens is becoming more likely (Waits et al., 2018). A hybrid approach that makes use of ABM will be crucial in slowing foot traffic to the Arctic's remote and isolated communities, helping mitigate disease transmission, and ultimately refining interdisciplinary Arctic science. As the Arctic undergoes extreme changes and as more researchers visit the region, including those who genuinely wish to co-produce needed science and those who view the Arctic as an "intriguing destination", the burden to communities will grow. ABM simulation should play a role in reducing the need for field work, subsequently limiting these harms while accelerating transparent, equitable, and co-developed policies for myriad benefits. Here, we enumerate several aspects of ABM that make it a particularly powerful tool for studying permafrost thaw.

2.2.4.1 ABM Accommodates Interdependent Permafrost Thaw Effects

ABM has been widely used to study complex systems due to its ability to represent several levels of interaction within a complex environment representation (Taillandier et al., 2012). Most ABMs now offer seamless integration with visualization platforms such as ArcGIS. For example, GAMA is a simulation platform which was first developed by a joint effort of the IRD/SU

UMMISCO and has now grown to include industrial partners and academicians worldwide (Taillandier et al., 2019). Several workflows can be built around such tools that not only address the complexities implicit in permafrost itself, but also the less obvious-but-significant emergent complexities which could lead to unwanted surprise (essentially, the unknown unknowns). By fully leveraging the workflows, programming, and unifying dialogues that ABM enables, scientists and stakeholders can collectively assess any challenge through both co-produced and Indigenous-led knowledge. Using ABM, planners and stakeholders can collectively navigate the complexity of systems and respond with appropriate policies (Zellner, 2008).

Permafrost thaw impacts many facets of the environmental landscape. These "primary impacts" are the ways in which permafrost thaw impacts the environment directly. As a result of these changes, human civilizations, and the resources they cultivate, or depend on, also change. These "secondary impacts" are impacts which permafrost has on human civilizations, through environmental changes. We suggest the primary impacts which pertain to environmental changes logically lead to the secondary impacts which concern disruption of human societal systems and lifestyles. Permafrost thaw implicates both primary and secondary impacts via the interaction of a vast range of variables from geophysics to atmospheric chemistry to cultural identities and local livelihoods to the ability to maintain and deploy military defenses. Examples of primary impacts include earth destabilization, coastal erosion, soil nutrient supply decline, climate warming, and systemic ecosystem changes. Examples of secondary impacts include resource scarcity, human relocation, disease spread, infrastructure damage, economic shifts, inability to move goods and resources, impaired defense readiness, and increased need for state and or federal resources.

Climate and environmental changes undoubtedly impact human civilization in many ways. Impacts that have been studied using ABM include migration (Thober et al., 2018), agriculture (Troost et al., 2012), conflict (Hailegiorgis et al., 2010), marine resources (Morrison & Addison, 2008), FEWS (Sawatzky et al., 2018), health and ecological functions via linear feedbacks

(Sawatzky et al., 2018), and many other facets of society. Secondary impacts are often tightly coupled, which further contributes to complexity. For example, prior work using ABM to study policy decision-making processes in urban areas has demonstrated a relationship between human land-use change and population trajectories (Kocabas & Dragicevik, 2013). As well, land-use change relates to the economy (both impacted by permafrost thaw in their own right), especially in coastal regions where land use decisions have been found to correlate with microeconomic motives (Filatova & Van der Veen, 2006). Secondary effects such as change in resource availability and regional conflict may appear to be independent, but in fact changes in sustenance are the root of increased tension in some cases (Hailegiorgis et al., 2010).

2.2.4.2 ABM Engages Diverse Stakeholders

ABM allows for a range of agent identity and flexibility that is needed when studying the effects of permafrost thaw in the Arctic. An agent can be a human, animal, or an abundance of other entities, each of which is modeled to be reactive, autonomous, proactive and temporally continuous (Graesser & Franklin, 1996). The study of permafrost thaw necessitates that the behavior of both people and animals be modeled. Climate and environmental changes in the Arctic are affecting wildlife in several ways, including, food availability, interspecies competition, predation, and increased human disturbances (Davidson et al., 2020). Human migration has been observed in many parts of the Arctic in response to adverse environmental and economic changes. One exception is Alaska, where there appears to be less migration (Huntington et al., 2017). This may be caused by attachment to a location, inability to move successfully, search for alternatives to moving, and reliance on methods which delay negative impact for the short term (Huntington et al., 2017). These regionally dependent behaviors must be considered during research and policy development to accurately represent the Arctic in an ABM.

2.2.4.3 ABM Enables the Forecasting of Equitable Futures

Beyond simply modeling diverse stakeholders, it is also necessary to engage them directly in scientific endeavors. A lack of understanding regarding complex human-environmental issues on the part of stakeholders puts them in position to blindly trust the insights generated by planning professionals and computer model outputs (Zellner et al., 2012). ABMs can be used to represent decision making and environmental dynamics while encouraging non-expert participation in the model development and interpretation stages, resulting in effective solution building (Zellner et al., 2012). When stakeholders are involved at this depth, insights on model results can lead to modifications which prevent inaccurate policy decisions (Zellner et al., 2012). ABM can also be beneficial as a collaborative planning exercise, helping stakeholders to understand and explore a range of possible outcomes (Zellner et al., 2012). Disaster recovery models have been used which do not consider the will or vulnerability of stakeholders (Eid & El adaway, 2017). When a bottom-up approach was implemented to inform the creation of an ABM toolkit which did take these factors into account, studies found there were higher disaster recovery rates specifically during restoration efforts in the aftermath of hurricane Katrina (Eid & El adaway, 2017). ABMs enable a wide range of stakeholder inputs, reflecting the plurality inherent in communities and the tensions between local needs, regional drivers, and national policies. In their Arctic Research Plan (2022-2026) the Interagency Arctic Research Policy Committee, an advisory committee spanning federal and local interests, lists “co-production of knowledge and Indigenous-led research” as a best practice (Interagency Arctic Research Policy Committee, 2020, p. 2). Using ABMs researchers can more easily ensure that more diverse stakeholders have input into scenarios development, feedback and corrections as the model is run. Serving as an inexpensive, accessible, and shared space, ABMs can foster collaboration and sustain transparent, shared understanding through exploration and dialogue.

Agent based modeling enables a wide range of interdisciplinary collaborators to contribute to and have oversight on simulation development. A quicker turnaround on hypothesis testing than other traditional methods could allow for more feedback and contributions from various groups. Serving as a boundary artifact that fosters collaboration, ABM helps interdisciplinary teams maintain a shared understanding. Drawing on ABM project experience involving political scientists, evolutionary biologists, computer scientists and economists, a set of propositions have been put forth detailing how ABM overcomes arbitrary boundaries between disciplines (Axelrod, 2006). One of those propositions states that ABM can reveal unity across disciplines (Axelrod, 2006), perhaps potentially concerning strategic interests between the Department of Defense and Tribal corporations. A model was developed to assess how scenarios associated with economic and climate change might affect the local economy, resource harvests, and the well-being of residents for the Western Canadian Arctic community of Old Crow, Yukon (Berman et al., 2004). The model integrates information from disparate sources and disciplines to generate a set of possible long-term futures with a richness and detail that would be difficult to achieve with other methods (Berman et al., 2004).

2.2.4.4 ABM Empowers Policy

ABM has been particularly beneficial when used in applications related to climate change, specifically concerning complex relations between international agreements and domestic policy outcomes (Gerst et al., 2013). In economics, ABM has been used to inform policy areas such as financial market dynamics, banking regulation, credit linkages, and monetary policy (Dawid et al., 2014). Toward a more social implementation, simulations of policy intervention impact enabled by ABM shed light on food deserts and the produce consumption of low-income households (Widener et al., 2013). Agricultural policy has also leveraged ABM analysis in recent years as a traditional microeconomic model (Kremmydas & Rozakis, 2018). The agent-based agricultural policy simulator, AgriPoliS, has made it possible to analyze agricultural policy reform results (Brady et al., 2012). ABM is useful in these domains because it can readily incorporate both environmental and behavioral parameters (Kremmydas & Rozakis, 2018). Addressing human-environment systems holistically through ABM enables the implementation of effective policies to address environmental issues (Zellner, 2008). The way in which ABMs can be used to accommodate complexity and uncertainty also makes them invaluable for environmental planning and policy creation (Zellner, 2008). Sustainability calls for a collective responsibility of environmental issues which can be facilitated by an ABM approach, including comprehensive and participatory analysis that enable communication between local and regional scales of policymaking (Zellner, 2008). ABM adds key adaptive capability to current modeling elements and is not to be considered stagnant, but continuously changing flexibly in response to natural, socioeconomic, and institutional conditions as new insight is gained in these areas (Zellner, 2008). Overall, simulation models provide value as social-ecological experiments that can synthesize interdisciplinary knowledge bases and support policy development (Iwamura et al., 2016).

The increased use of ABM to study permafrost and other Arctic phenomena is critical for advancing the state of Arctic research and protecting Arctic communities. Although there is often an overt emphasis on fieldwork, there exist a wealth of opportunities in which ABM can be used synergistically with fieldwork to rapidly advance scientific understanding, while protecting Indigenous communities from potential harms. Several aspects of ABM are particularly well-suited for permafrost research. These include the ability to accommodate interdependent effects, the possibility to engage diverse stakeholders in model construction and validation, the projection of equitable future scenarios, and the empowerment of policymakers to effect change in precise and informed ways. Perhaps most importantly, the hybrid use of fieldwork and ABM stands to accelerate transparent, equitable and co-developed science and policy while helping to reduce the potential for adverse effects on local communities. In other words, ABM can enable Arctic permafrost work that is both *better* and *safer*.

2.2.5 Design for Evidence-Based Decision-Making

This thesis supports that ABM is a decision-maker tool which empowers the prioritization of stakeholder input. Co-production of knowledge, when following the 11-steps to ABM, is not afterthought, but a part of the process of an ABM's validation. However, the ABM central to this thesis is not the first decision-maker tool to be produced for the North Slope Borough. In Utqiaġvik, sea ice decision support tools have been co-produced which are intended to link Arctic system science research to decision maker needs (Kettle et al., 2019). The purpose of these tools is to improve situational awareness and crisis response so that risks associated with sea ice and environmental-related hazards in the Arctic are reduced. A key challenge of using Arctic system science research to support decision-maker needs, much like what the PIPER NNA project intends to do, is the logistics of operating and maintaining near-real time observations. The many futures predicted by simulation modeling, such as ABM, might offload such burden and better empower decision-makers. A decision support tool puts power in the hands of decision-makers, which might minimize the effects of special interests in the Arctic (oil, gas, etc.) which seem often take precedent over community wellbeing. Achieving a "bottom-up" approach to both personal and community resilience, according to the Arctic Council, requires the empowerment of those who may be less likely to have – or do not believe they have – a voice, to develop agency in matters that impact them either directly or indirectly, as Trump et al. (2020) asserts. Designing decision-maker tools, such as ABMs, could be very helpful in halting the "fleeting window of opportunity to cultivate the strong bottom-up resilience culture that has been built over centuries of Arctic life…" (Trump et al., 2020).

> "Arctic cultures have rich histories of adaptation based upon generations of life shared in unique places. Today, their natural and socio-economic environments are changing at unprecedented rates, drawing swarms of new stakeholders in the form of immigrants, interested neighbors, and interlopers with political and economic ambitions. The complex nature of change and corresponding disruption to static quo present a fleeting window of opportunity to cultivate the strong bottom-up resilience culture that has been built over centuries of Arctic life, rather than ceding to centralized direction that has evolved in more heavily populated and technologically developed regions." (Trump et al., 2020, p. 405)

A survey conducted by Arctic researchers revealed that participants in Point Lay, Wainwright, Utqiaġvik, and Kaktovik deemed the information in the following five aspects as crucial for their community planning for continued climate warming: natural environment, built environment, cultural awareness, education and communication, and *policy* (Liew et al., 2022). Listed below is information regarding policy that is deemed important, according to the survey participants, for planning for the future (Liew et al., 2022).

- Funding
- Flood insurance
- Coastal zonation and management
- Wetland protection and restoration
- Scientifically supported management
- Increased government input
- Diversified investment mechanisms
- Low-emission vehicles
- Improved environmental governance

- Quantitative evaluation systems for
  coastal wetland degradation and restoration

According to these policy-related priorities, the residents of the four coastal communities have various roles they would like to see their political leaders fulfilling and have even expressed a need for increased government input. As Pierra Mendes-France famously said, “To govern is to choose,” (The New York Times, 1974) meaning decision-makers face the burden of deciding how these coastal communities will move forward with whatever information available to them. For this reason, decision-support tools are important because they inform decision-makers and heighten their capabilities to *choose well*.

Where there are tools that simulate people, intended to be used by people to make decisions that impact people, it is best to follow human-centered design practices. The model in development as the focus of this thesis has been designed with the user in mind and will be helpful enough to cover insights policy makers need most. A policy maker, and community decision-maker, will be able to use this model to answer questions such as:

- If I vary water resources, what does that do to community health over time?
- Does the cost of infrastructure justify the increased community wellness?
- What happens if we have 1 large water resource instead of 10 small water resources in this region?
- What are community strain conditions as compared to what repairs and maintenance are required?
- What does a community need to repair itself; can a community be too damaged to support repair?

2.3 ABM and Community Resilience

Agent-based models have been used to study socio-ecological systems in Arctic regions before. For example, the MASON Northlands ABM relates ambient and soil temperature increases to measurable social impacts, mediated by biophysical effects of climate change on the built environment, as in a coupled human-artificial-natural system (Revilla, 2015). Adaptation and sustainability in a small Arctic community has also been studied using an agent-based simulation model. This model assesses how scenarios associated with economy and climate change might affect the local economy, resource harvests, and the well-being of residents for the Western Arctic Canadian community of Old Crow, Yukon (Berman et al., 2004). Agent-based modeling is also a promising methodology for evaluating and testing resilience-related measures (Brudermann et al., 2016). Seismic resilience of an electric power supply system was quantified using an agent-based framework (Sun et al., 2019). ABM has also been used to simulate post-disaster recovery in the aftermath of Hurricane Katrina, resulting in an overall sustainability plan to be put in place for three Mississippi coastal counties (Eid & El adaway, 2018). Another model, The PEOPLES framework, incorporates four types of resilience (technical, organization, social, and economical) and four attributes (robustness, redundancy, resourcefulness, rapidity) outlined by Cimellaro et al. (2016) and Brueau et al. (2003) respectively to create a hybrid model that includes agent-based modeling (Melendez et al., 2021). It is intended to be beneficial to decision-makers under emergency situations due to its ability to identify different resilience aspects of a community. This framework has been applied to the city of San Francisco after the 1989 Loma Prieta Earthquake and showed a need for better resilience in facilities compared to lifelines (Kammouh et al., 2019). The POPLES framework was also applied to Harland County, Kentucky, a rural Appalachian region. Here, it was used to quantify community resilience after a severe flooding event (Melendez et al., 2021). Marasco et al. proposed a platform that would unify ABM with other sources of information and ultimately assess resilience of a community by modeling the interdependency between buildings and road and water, power, and transportation networks (Marasco et al., 2021). Agent-based modeling is not new to studies of resilience, nor to helping community decision-makers respond to emergency situations.

Chapter 3[8]

Best Practices for Agent-Based Modeling

This chapter synthesizes principles for the use of ABM in engineering design. These principles influenced the design process followed in development of the NNA PIPER ABM centric to this thesis, which is discussed in Chapter 4. Section 3.3 details how the design thinking process and the principles for ABM in engineering design are comparable and were both followed in design of the NNA PIPER ABM. Further, section 3.3 highlights which chapters of this thesis discuss various stages of both design processes.

The specific objectives of this chapter are twofold. The first objective of this chapter is to summarize a review of current ABM research in engineering design, with a specific focus on models used to simulate human systems in engineering design context. The second objective of the chapter is to contextualize each of the steps with respect to a literature review, identifying heuristics and best practices. Through this contextualization, gaps in current practice are identified.

To meet the research objectives, a qualitative analysis of agent-based models in engineering design was conducted using a literature survey approach. For the scope of this study, only ABM for simulation of human systems in engineering design was considered. The intent of the literature survey was to firstly uncover the extent agent-based models in engineering design follow systematic steps for modeling and simulation, and lastly, highlight existing gaps in approaches to ABM in engineering design.

[8] This chapter is based on work that was submitted to the ASME IDETC (Agyemang et al., 2022). The author of this thesis contributed to the overall writing of that paper and specifically led several sections.

3.1 Overview of ABM and Engineering Design

The work in this thesis follows both the five-step design thinking process (empathize, define, ideate, prototype, test) (Aquino, 2017) and 11-step approach to modeling and simulation outlined by Maria (1997) (see Table 3.1 for the 11 steps). While use of ABM in engineering design continues to grow, there are few resources specific to engineering design that guide how to develop an ABM, execute an ABM experiment, and assess the subsequent results. This inhibits the effective use of ABM by design researchers who are new to the methodology. The goal is to provide a resource for both novice and experienced design researchers that details a systematic approach to ABM. First, this chapter reviews current ABM research in engineering design, with a specific focus on models used to simulate human systems. Specifically, this work was reviewed with respect to a step-by-step approach to modeling developed in the systems simulation literature. Second, each of the steps is contextualized with respect to the literature review, identifying heuristics and best practices which can be found in section 3.2. Through this contextualization, gaps in current practice are also identified.

Agent-based modeling (ABM) is a powerful approach for computationally modeling and simulating various types of systems (Macal & North, 2009; Bonabeau, 2002; Gilbert, 2008). In ABM, software agents execute various behaviors by assessing their situation and making decisions based on a set of rules. A typical agent has a set of micro-level attributes, behavior rules, memory, resources, decision-making sophistication, and rules to modify behavior rules throughout the simulation (Macal & North, 2009; Bonabeau, 2002; Gilbert, 2008). A collection of simulated agents can then be used to study the emergence of macro-level systems dynamics. ABM is applicable to a wide range of fields, enabling users to gain insights into phenomena that are difficult to study in the real world due to challenges of feasibility and ethical constraints (Bonabeau, 2002; Kimbrough, 2011; Macal, 2016; Macal & North, 2010; Hammond, 2015; Perišić et al., 2018; Ameen, 2019). ABM capabilities are applicable to a variety of social, physical, and economic systems (Macal &

North, 2009; Bonabeau, 2002; Gilbert, 2008). This capability makes ABM extremely valuable in studying phenomena in engineering design (McComb & Jablokow, 2022), such as the interactions between members of a team.

With ABM being such a powerful approach, there have been many resources that provide guidance on ABM in general applications (Bonabeau, 2002; Kimbrough, 2011; Macal, 2016; Macal & North, 2010; Hammond, 2015; Perišić et al., 2018; Ameen, 2019). Current publications on ABM guidelines provide general information on the benefits of ABM, common pitfalls, applicable fields for ABM, tools, language, approach, and descriptions of agents and agent behaviors across various fields (Gilbert, 2008; Macal & North, 2005; Bonabeau, 2002; Abdou et al., 2012; Kimbrough, 2011; Helbing & Balietti, 2012). The majority of publications that guide users on ABM include sections that define and detail the benefits of ABM as well as the fields where ABM can be applied (Bonabeau, 2002; Kimbrough, 2011; Macal, 2016; Macal & North, 2010; Hammond, 2015; Perišić et al., 2018; Ameen, 2019). Some literature even goes as far as to detail specific types of cases and scenarios where ABM can be used or was used. While this high-level information is helpful, there is also a need for less abstract information that helps a beginner accurately apply ABM concepts. This works looks to further close that gap and serve as a resource that provides procedural guidance on the use of ABM in engineering design research.

3.2 Review of Principles for ABM in Engineering Design

ABM applies to many areas in engineering design, so narrowing the scope to the simulation of human systems made it possible to highlight and compare practices within a similar context. To highlight the extent to which engineering design agent-based models follow systematic steps for modeling and simulation, this work makes use of Maria's approach for modeling and simulation (Maria, 1997). Maria (1997) provided an 11-step approach to modeling and simulation which includes systemic steps and aspects that are crucial for effective modeling and simulation.

Specifically, the approach identified 11 steps for developing a simulation model, designing a simulation experiment, and performing simulation analysis. These steps align well with the general approach typically take when constructing an agent-based model, and therefore form a strong backbone for assessment of extant literature in this work. Table 3.1 below displays 11 steps by Maria (1997) and the criteria based upon which each step was evaluated.

Table 3.1. Evaluation Metric[9]

Step	Criteria: The paper details…
1. Identify the Problem	…the problem being studied.
2. Formulate the Problem	…the components of the problem.
3. Collect and Process Real Systems Data	…acquisition and use of data from real-world scenarios.
4. Formulate and Develop Model	…how the model construction.
5. Validate Model	…approach to model validation.
6. Document Model	…location of model documentation and supporting literature.
7. Select Appropriate Experimental Design	…design of experiments and justification.
8. Establish Experimental Conditions	…parameters for simulation runs.
9. Perform Simulation Runs	…approach to simulation runs.
10. Interpret and Present Results	…meaning of model outputs and formally presents findings.
11. Recommend Further Course of Action	…next steps based on research findings.

The literature search and screening resulted in 22 papers for the analysis. To address the first research question, each paper was evaluated against 11 systematic steps for modeling and simulation outlined by Maria (1997). Based on this assessment, it becomes clear that while many procedural steps are well addressed in the engineering design community, several are underreported

[9] Adapted from ASME IDETC (Agyemang et al., 2022)

in the literature (namely collecting and processing real systems data, validating the model, and documenting the model). However, none of the steps are satisfied by every one of the modeling papers reviewed here. Therefore, using the findings from the literature survey, best practices are suggested for agent-based models in engineering design across each of the 11 steps proposed by Maria (1997). Also provided is additional detail on the three steps that are under-reported in the engineering design literature.

3.2.1 Identify the Problem

Initializing the development of an agent-based model begins with identifying the problem the model will address. Maria (1997) defines this first step, *identify the problem* as “Enumerate problems with an existing system. Produce requirements for a proposed system.” Commonly, in ABM, the existing system is some human process or a previous agent-based model and identifying the problem requires extensive knowledge of the current system. An extensive literature review of common practices and research within the system is essential as it shapes an understanding of the system’s capabilities and outcomes.

When developing an agent-based model to simulate teamwork in engineering systems, for example, a comprehensive understanding of the processes of engineering teamwork should be realized. Crowder et al. (2012) address this step well in their discussion the complexity of teamwork in engineering systems, noting cognitive processes such as social interaction and communication. In tandem with referring to the literature, researchers commonly provide a review on the other ABM or simulation methods that have addressed this system. As an example, Lapp et al. (2019b) and McComb et al. (2015) discuss previous agent-based models of teamwork such as the CISAT model and contextualize the contributions of their work with respect to that review.

Using this comparative knowledge, one may begin to identify gaps or problems within the existing system. Thus, new paradigms within the system or new opportunities for research may emerge and the requirements of an agent-based model to address these problems materialize. This motivation may also respond to broader needs within a research field. For instance, in their work on agent-based models in psychology, Reuter et al. (2018) highlights the challenge of simulating psychological studies and proposes an ABM to meet that challenge.

3.2.2 Formulate the Problem

Following identification of the problem, formulation of the problem is the next stage in developing an effective agent-based model. Maria (1997) highlights this stage *formulating the problem* to define the inputs and outputs of the proposed system, including the performance metrics and end users. Brief configurations of interests and hypotheses about the system are introduced. Proper formulation of the problem outlines the variables of the proposed system derived from the data collected in the research review. One technique that can be used to aid in problem formulation is *Pattern Oriented Modeling* (POM)—a set of strategies for using patterns observed in the systems to ensure that an ABM captures the right “essence” of the system (Grimm & Railsback, 2012). This technique is foundational for problem formulation, as it starts with identifying multiple patterns of behavior in the real system that seem to capture the essential internal mechanisms for the problem being modeled. It should be possible for the model to reproduce each pattern by adding some state variables and processes. This increases the complexity of the model in structure such that it can be tested against multiple patterns (Grimm & Railsback, 2012).

Formulation of the problem contextualizes and offers relationships between the variables of the proposed ABM. These relationships are often represented using real systems data, which informs the formulation and workflow of the model. In their work, Syal et al. (2020) highlight that the landowner acquisition period in wind farming is highly uncertain. Thus, they develop an ABM to investigate the evolution of landowner and developer decision making over time. To formulate this problem, the authors incorporate two classes of agents: the landowner and the wind developer, and two monetary values: a compensation rate and a minimum acceptance value. The authors create a model framework in which landowners decide to accept or reject the offered compensation rate, influenced by developer actions. The model then outputs the number of landowners who accept the contract over time for different scenarios.

3.2.3 Collect and Process Real Systems Data

The third step of developing a simulation model is to collect and process real systems data. Maria (1997) defines this step as the opportunity to (1) collect data on system specifications, input variables, as well as performance of the existing system, (2) Identify sources of randomness in the system, and (3) select an appropriate input probability distribution for each stochastic input variable and estimate corresponding parameter(s). In the review of the literature, less than half collected and processed real systems data. Han and Peng (2019) is an example of how most literature discussing ABM briefly mentions where the data used in model development was sourced before directly transitioning into a “Methods” section that, at best, loosely explains input variables, performance of the existing system, etc. If authors feel as though this detail is adjunct to the body of their publications, then a more in-depth summary of input data can be included via an external appendix, as Wens et al. (2020) has done following the ODD + D protocol for AMBs as described by Muller et al. (2013). Data collection is fundamental to the validity of a model because of its role in eliciting the behavior of agents in ABMs. Methods such as scenario-based questionnaires, the benefits of which are discussed by Utomo et al. (2022), can help increase an ABMs validity by relating more closely to respondents’ actual decision-making process. Despite the recent proliferation of large-scale behavior data that can be used to empirically develop agent-based models, literature has neglected to offer a structured ABM approach to produce agents or its parts directly from data (Kavak et al., 2018). A structured way to integrate big data and machine learning techniques at the individual agent-level could advance the development of empirical ABMs and conduct their validation (Kavak et al., 2018). Perhaps as we see more of big data driven ABM there will be stronger focus on the opportunities Maria (1997) has defined for collecting and processing real systems data, as Lu et al. (2021) has done, even though this may the beneficial result of an urge to justify the use of a big data platform.

Ethical dimensions of data collection are important to consider when collecting data to aid in the construction of an agent-based model. Data privacy and other ethical issues are emerging concerns (Stahl & Wright, 2018), and therefore ethical issues involving data may be challenging to resolve because data and data science are ubiquitous, have the potential to impact all aspects of life, and partly because of their intrinsic complexity (Hand, 2018). However, emerging work offers summary guidelines that provide guidance on how best to use and operationalize data. For instance, Jobin et al. (2019) provide a review of the global landscape of AI ethics guidelines, identifying convergence around a unifying set of principles (transparency, justice and fairness, non-maleficence, responsibility, and privacy). Although ABM is not identical to AI, many of the same principles can guide effective modeling practice.

When constructing an agent-based model and collecting real systems data, one approach is to align with ethical guidelines provided by the relevant professional society. Professional societies typically have their own formal code of practice based on ethical principles. However, it is important to note that there is no single professional society for modern data science and therefore different application domains will map the principles to practical ethical guidelines in different ways (Hand, 2018). Hand (2018) mentions functions of ethical codes for data collection, manipulation, and use, and references Drew’s six main principles for data science in government (Hand, 2018; Drew, 2016). A consequentialist approach to ethics when modeling is recommended by Palmer (2017) who also states the importance of shifting ethical considerations from the behavior of the modeler to the model itself and the model’s inherent uncertainty.

One of the “outward facing” purposes of general ethics codes that Hand (2018, p. 178) lists is “protect vulnerable populations who could be harmed by the profession’s activities.” Marginalized communities, or vulnerable communities, may be impacted to a greater degree by the practices of data collection than other groups, and an example of this which can be seen currently is the relationship between Indigenous peoples and AI. ABM has often been used to study socio-ecological systems (Hicks et al., 2021). Indigenous peoples make up less than 5% of the world’s population, yet their traditional lands are home to 80% of the world’s biodiversity (Jensen et al., 2020). Jensen et al. (2020) offer that any framework developed for a digital ecosystem for Earth should affirm Indigenous peoples’ rights and that it is imperative to engage, learn from and co-design digital solutions with Indigenous communities. Lewis (2020) provides an Indigenous Protocol and Artificial Intelligence Position Paper. Ethical considerations regarding the consequences of data collection for existing vulnerable communities is paramount, but ethical considerations are best made when extended to all potential stakeholders. Stahl and Wright (2018) state mechanisms to address ethical issues must involve stakeholders, including civil society, to ensure that these technologies’ benefits outweigh their disadvantages. As the engineering design community continues to address global challenges (e.g., climate change (Hicks et al., 2021)), it is necessary to ensure that these vulnerable populations are not taken advantage of.

3.2.4 Formulate and Develop Model

Given the outlined variables and their statistical processes, a conceptual formulation of the model may begin. The purpose of model formulation is to produce a conceptual understanding of the model mechanisms by translating conceptual processes from the real system into a model framework (Maria, 1997). This ensures that the model is consistent with the workflow of the real system. Flow diagrams and illustrated frameworks are popular ways of executing this step in that they help to visually explain the sequence of the model workflow. These workflows may take on different schemas and in practice they can be depicted in varying ways such as the methodological or simulation framework (Stavrakas et al., 2019) or as an overview of the modeling methods (Hulse et al., 2019).

One way to develop a model workflow is to consider the sequential processes of the model from inputs to outputs. Crowder et al. (2012) provide illustrations in their work that depict the model workflow in terms of engineering design processes. They explain the division of higher-level tasks into subtasks which is undertaken by a single agent (Crowder et al., 2012). Singh et al. (2021) also provide visual representations of the model workflow and framework. To emulate real co-design practice, the model starts with multiple sessions of collaborative idea generation and idea selection (Singh et al., 2021). The workflow continues with a final solution proposed to the lead agent, whose feedback helps the agents to learn and accordingly propose solutions in the following session (Singh et al., 2021).

During development, it is critical to verify that the model executes as intended. According to Maria (1997), verification techniques include traces, varying input parameters, or substituting constants for random variables. Verification of an ABM is important as they are typically used to model complex phenomena (Niazi et al., 2010). Leykum et al. (2012) verified their model of clinical systems by iteratively refining the parameters based on the results of the data collection period. As these refinements were being made, the dynamics of the model were updated (Leykum et al., 2012). Niazi et al. (2010) provides a formal approach to verification of agent-based models based on building a companion multi-agent system, the Virtual Overlay Multi-Agent System (VOMAS) (Niazi et al., 2010; Niazi et al., 2017). These methods of model verification provide strong examples for model verification against real system data during development.

3.2.5 Validate Model

The fifth step in the process concerns the assessment of the validity and representativeness of the model's output with respect to the real system's output under known input conditions. At this point of the ABM development process, it is pertinent to perform additional test simulation runs of the ABM under atypical and extreme conditions. These tests have one goal: to *break* the model and establish its range of valid use; this is the essence of validation (Miller, 1998). There are a variety of approaches that can be used to accomplish this goal.

The validity of any computational model can be analyzed across four main aspects: sources of data, conceptual model, simulation model, and operational behavior (Sargent, 2013):

- Data validity: the degree to which the input data for developing and testing the model and conducting simulation experiments is accurate, appropriate, and sufficient.
- Conceptual model validity: determines whether the underlying theories and assumptions are correct and the causal relationships in the model are reasonable for its intended purpose.
- Simulation model validity: evaluates the correctness and internal consistency of the programming and implementation of the conceptual model using a simulation language.
- Operational validity: assesses whether the output behavior of the simulation model meets the required level of accuracy and robustness over its domain of application.

Validation of ABMs on each of these aspects can prove to be a tough task depending on how much detail is used to trace individual agent behavior and how complex the emerging global behaviors can turn out to be (Bryson et al., 2007). Also, one type of validation does not necessarily replace another. The preservation of data validity can be particularly difficult for agent-based models aimed for exploratory analysis, where the input parameters around or their intervals are not well-defined. This can be particularly difficult for the preservation of data validity in agent-based models aimed for exploratory analysis where the input parameters abound, or their intervals are not well-defined. Developers of ABM for social simulations are inclined to favor the keep-it-simple-stupid and Occam's razor (or "parsimony") principles by arguing that the most enriching system-level behavior is the one that is as product of simple micro-level rules (Sansores et al., 2006). On the other extreme, empirically-grounded ABMs—namely, those who are purely data-driven—are criticized for their lack of parametrization at the individual agent level which affects transparency (Sun et al., 2016). For these reasons, validation of ABMs tends to be subjective and rely on the opinion of knowledgeable individuals (i.e., "face validity"), animations and graphics, and comparisons with macro-level models.

One example of ABM that uses face validity in the form of literary evidence is provided by Meluso et al. (2020). Their work describes an ABM model that studies the impact of miscommunication on the performance of a complex system design process, where the agents represent designers across different disciplines. Miscommunication is characterized by the emergence of deficiencies in the design process as a response to variations in how current the information that design agents exchange is, ranging from "current" (the actual state of the design of their subsystem) to "future" (projected design). The model provides insights on how an engineering design organization's valuation of both types of estimates could negatively impact design performance. Face validation compared the results from the model with practitioners' experiences that see miscommunication as a product of the designers' lack of agreement on how "good estimates" are defined. As Meluso et al. (2020) discuss, the next iteration of this model requires additional real system data (Step 3) to refine the formulation of the model (Step 4) and reach higher levels of operational validity.

It is possible to assess the operational validity of an ABM by comparing its output with that of other models. Using a toy problem of collaborative paper writing, Baldwin et al. (2015) discuss how a top-down discrete event simulation can be used to back up the macro-behavior emerging from simulation of the ABM. Due to their closer adherence to observable system data, simulation of events-based models also provides an avenue to evaluate the empirical validity of an ABM. They can also be used as a complementary step to refine the outcomes from Steps 3 and 4 or be integrated into the ABM itself (Shafiei et al., 2016).

Nevertheless, it is important to emphasize that validation of any model must be tied to the specific questions that the researcher wants to address, and thus the use of an ABM should be coherent to the target level of granularity that such questions demand. In this regard, ABMs have the potential to not only test hypotheses about how macro-aspects of human behavior in design are affected by individual design decisions but also contribute to hypothesis generation and conceptual understanding of complex dynamics (Oliveira et al., 2019).

3.2.6 Document Model

A key factor that determines the success of a research finding is the extent to which it can be reproduced (Janssen et al., 2020). Effective documentation is hence a crucial step in communicating scientific findings with readers in a manner that is easily comprehensible. When describing Agent-Based Models specifically, proper documentation can help readers understand and evaluate the model (Grimm et al., 2010), reproduce results from the model (Grimm et al., 2006), and make additions to the model without having to reinvent it. In fact, a study analyzing 7500 individual-based and agent-based models found that, in 2018, only 18% of models proposed in the top 10 most popular fields included some level of documentation (Janssen et al., 2020). Although this study demonstrated an upward trend in research papers making strides towards documentation of code, there still seems to be a lack of documentation that is accessible to the community in the long run. The current work shows that this trend of ineffective documentation practices continued. While most papers attempt to explain their proposed ABMs using mathematical equations, flowcharts, pseudocode, and other approaches there seems to be a gap in the availability of papers that describe ABMs in a manner that is facilitate model reproduction by the community. This gap in documentation could be explained by the lack of standardized documentation practices.

To streamline the process of documenting Agent-Based Models, the Overview, Design Concepts, and Details (ODD) Protocol was developed by Grimm et al in 2006 (Grimm et al., 2006). This protocol was intended for Individual-Based and Agent-Based Models proposed in the field of ecology. It was hence adopted as a recommendation by the CoMSES Network, "a network for computational models with applications in social and ecological sciences," in 2007 (CoMSES Net, 2022). This protocol outlines 3 elements that help the reader understand the general purpose of the model and its functioning: Overview, Design Concepts, and Details (Grimm et al., 2006).

For the first element, Overview, Grimm et al. (2006) propose 3 sub-sections that describe the purpose of the model: purpose, state variables and scales, and process overview and scheduling. Within Purpose, the paper should provide a concise description of why the Agent-Based Model was created and help the reader understand its general application (Grimm et al., 2006). As part of State Variables and Scales, the overarching structure of the ABM should be described. The structure could include descriptions of what entities were created for the model, how these entities were characterized, justification for how they were chosen, and the environment in which they were placed (Grimm et al., 2006). In Process Overview and Scheduling, the ODD protocol suggests including the description of relationships between agents, the order in which variables within the model are updated, how time is handled within the model, etc. (Grimm et al., 2006). The goal of the Overview section is to provide the reader with the information required to set-up a skeleton of the ABM using object-oriented programming.

The second element, Design Concepts can be subdivided into Emergence, Adaptation, Fitness, Prediction, Sensing, Interaction, Stochasticity, Collectives, and Observation (Grimm et al., 2006). The ODD protocol dictates that these subsections can be rearranged and omitted based on the complexity of the model being documented. Each of these proposed sub-categories have been explained in more detail in the research paper published by Grimm et al. (2006).

Finally, the third element of the ODD protocol, Details, suggests that researchers cover topics of Initialization, Input, and Sub-models within this section (Grimm et al., 2006). As part of Initialization, the protocol suggests that researchers describe the initial values of state variables, how these values change with the functioning of the model, and how these decisions were justified. Within Input, readers should be provided with information about what data or conditions are needed to run the model and how this data was generated or acquired. After this section, readers should have the knowledge needed to generate or acquire the inputs described (Grimm et al., 2006). Lastly, the section of the protocol that goes over sub-models should delve deeper into the mathematical equations used within the ABM, how these equations were derived, and a detailed description of all variables used in the model going over how these play a role in the behavior of the agents. The creators of this protocol also suggest making the source code of models available to readers using online archives or other tools that can be accessed by the public. For more information about this protocol and to examine a sample application of the ODD protocol, please refer to the paper published by Grimm et al. (2006).

While the ODD Protocol was developed specifically for the field of ecology, it provides some great pointers on how Agent-Based Models should be documented. Due to the broad nature of the 3 elements described within this protocol and the fact that ABMs in Engineering Design share human-subjects modeling in common with many ecology models, the ODD protocol could also be used as a reference for documenting ABMs in Engineering Design.

However, when using this protocol to document ABMs in Engineering Design, some additional steps must be outlined for best practices to follow when making source code available to readers. This is because when papers describing ABMs with applications in Engineering Design were analyzed, it was found that there were few papers that provided readers with access to the source code of the model, and even fewer that provided adequate information for readers to implement the model themselves.

In addition to the elements and sub-categories highlighted by the ODD protocol, effective documentation can be achieved by making the source code of Agent-Based Models available to readers wherever possible. There are a variety of resources available that allow researchers to share code. GitHub, Dropbox Paper, Bit.ai, etc. are some common websites that can be used for this purpose. Once the source code is made available, information described in the Input and Information subsections of the ODD protocol should help readers access or generate the required data and variables to implement the model. In addition, it is also typical for most libraries containing source codes, to include a “Read Me” document. This document, as seen in some papers describing ABMs in Engineering Design (Lapp et al., 2019b; Hulse et al., 2019; Grogan et al., 2018), typically includes information about how to run the model.

Providing readers with access to the source code of the model wherever possible, in conjunction with the ODD protocol can pave the way for effective documentation of ABMs in the field of Engineering Design.

3.2.7 Select Appropriate Experimental Design

The next stage in creating an effective agent-based model is to design simulation experiments, starting with selecting an appropriate experimental design. Experimental design refers to the systematic procedures or approach used to investigate and test the hypothesis (Lundstedt et al., 1998; Kelton & Barton, 2003). Maria (1997) highlights that when selecting an appropriate experimental design, several factors needed to be identified: a performance measure needs to be identified, input variables that influence the performance measure need to be selected along with the degree of each input variable, and the experimental design needs to be documented. Based on this measure, many agent-based models for simulation in engineering design reviewed in the literature survey present an experimental design, but few publications thoroughly document the selected experimental design used and provide justification (Perišić et al., 2018; Crowder et al., 2012; Lapp et al., 2019b; Reuter et al., 2018; Sosa & Gero, 2005; Zadbood & Hoffenson, 2017; Bell & Mgbemena, 2018; Raoufi & Robinson Fayek, 2018; Marley et al., 2017; McComb et al., 2017; Salamanca et al., 2019; Gabora & Tseng, 2017; Bhattacharyya & Ohlsson, 2010; Singh & McComb, 2021; Herath & Homberg, 2017; Lee & Malkawi, 2013; Lapp et al., 2019a; Hulse et al., 2019; Campbell et al., 1999; Soria et al., 2018; Grogan et al., 2018; Grogan et al., 2015; Meluso et al., 2020). To address this gap, a more systematic approach in experimental design needs to be taken. Kelton and Barton (2003) suggest the designer should (1), identify the purpose of the model, (2), identify the relevant output performance measures, and (3) identify sensitivity of outputs to inputs.

First, a clear, specific statement on the purpose of the model. This helps understand the model's intentions as well as the outputs of the model and how the data from the model can be interpreted. Stating a clear purpose of the model helps to identify the model scope as well as start the process for selecting an experimental design that is effective. This will also help in expansion of the model to address future research questions (Kelton & Barton, 2003). The purpose of the model can fall within various goals, including, but not limited to, validation, screening, understanding, sensitivity analysis, predictive modeling, or optimization (Kelton & Barton, 2003).

Next, is to identify the relevant output performance measures; information that results from the simulations. It is important to ensure the outputs the model provides are relevant to the goal of the study. The number of outputs can vary with length of simulation runs and other factors, so it needs to be determined which outputs, and how many outputs provide sufficient information relevant to the model purpose and goal. Identifying the relevant outputs can be done by narrowing down the outputs based on the model’s research questions or objectives. This ensures the inputs and outputs fit within the scope of the study supporting appropriateness of the experimental design.

The last step in selecting an appropriate experimental design is to identify sensitivity of outputs to inputs. Simply put, this means understanding the relationship of model outputs to model inputs. Model input and outputs can be qualitative or quantitative. To develop a model that effectively addresses the project purpose, the model must incorporate the inputs and variances in inputs affects the outputs being investigated. Agent-based model capabilities allow for qualitative and quantitative relationships between inputs and outs to be simulated. To take advantage of these capabilities, the model needs to correctly represent the relationships and dynamics between the inputs and outputs. These relationships need to be represented while still being within the scope of the study. Limiting the relationships representing the scope of the study supports the appropriateness of the experimental design. Relationships used to represent the inputs to outputs sensitivity should be supported by literature. Within a model, the relationships are usually represented using mathematical equations. The mathematical functions representing sensitivities should be based on literature-backed assumptions or literature supported relationships and trends.

The study by Meluso et al. (2020) indicates information to suggest an appropriate experimental design was selected. In this work, they clearly state the purpose of the model and identify the relevant output performance measures for the model. Ultimately, providing the purpose of the model, the relevant output performance measures, and the sensitivity of outputs to inputs shows the experimental design supports the research questions and experimental methodology align with the research objectives.

3.2.8 Establish Experimental Conditions for Runs

Test simulation runs of the model advise the definition of appropriate bounds for the model parameters and projected execution time with respect to available computational resources. The terminating conditions need to be advised by the level of granularity of the response variables (i.e., micro-, meso-, or macro-) and whether their convergence is of interest. For instance, in a work by

Zadbood and Hoffenson (2017), the transient response obtained from the simulation of an ABM of an automobile market system is used to highlight the versatility of the model to produce performance profiles—fuel economy, price, sales, and profits—under different input producer agents, consumer agents, policy (tax) conditions and identify opportunities for refinement. Subsequent work by Zadbood et al. (2019) expanded on the definition of the customer model's agents to inquire into the effect of word-of-mouth referrals on customer preferences (micro-level) and market performance (macro-level). This latter work also addressed the differences in steady-state response across market scenarios with and without referral effects.

Another key consideration in the definition of experimental conditions is the stochasticity of the system model and the number of independent runs. Most ABMs use stochastic components to describe the agents and, in some cases, the environment. Process generators to produce pseudo-random number streams with specific probability distributions are essential for the reproducibility of results. Assurance with respect to steady-state macro-level outcomes requires consistent convergence criteria for termination coupled with a minimum number of runs—between 30 and 50 as a general heuristic (Abdou et al., 2012). Nevertheless, it is good practice to set target confidence intervals or variability thresholds around the means or medians of the response variables and refine the minimum number of runs needed using the central limit theorem or comparisons between output distribution plots across different sets of inputs. Increasing the number of runs is usually a safe alternative to reduce variability and improve confidence in the results.

3.2.9 Perform Simulation Runs

Step 9 carries out the experimental plan described in Steps 7 and 8. In preparation for this step, ABM developers should establish a plan for collecting and recording output data. It is important to be mindful of the computational resources available to avoid running out of storage or working memory and cause the computer to crash. This is a common issue when using multi-purpose software platforms or running experiments for too long. Automatic logging of structured or unstructured output data at regular intervals during the execution is one of the mechanisms that ABM software libraries implement to safeguard simulation experimental results and it is a good practice for computational model developers (North, 2014). Logging for ABM models that are developed using general-purpose programming languages can be supported by compatible source available document-based database services; these services expedite the storage and querying of formatted logged data (Grogan et al., 2015). Prior to the execution of batch runs and informed by simulation tests, researchers should ready post-processing of the logged data for subsequent.

With the increased availability of advanced computing infrastructure (e.g., computing clusters and cloud resources), it is possible to speed up and simultaneously execute several batches of simulation runs. Large-scale ABMs can benefit from the use of a multithreaded framework to simulate concurrent agents' actions. If multiple processing cores are available, multithreading allows for parallel execution of agent threads (Welch & Ekwaro-Osire, 2010). As addressed in Step 8, the need for computing resources to run an ABM simulation should be balanced against the scope of the research and the variability threshold as some of these technologies can have a huge impact on the cost to the target users and negatively impact the reproducibility of results (Parry & Bithell, 2012).

3.2.10 Interpret and Present Results

In this step Maria (1997) suggests that one should "Compute numerical estimates (e.g., mean, confidence intervals) of the desired performance measure for each configuration of interest." and "Test hypotheses about system performance. Construct graphical displays (e.g., pie charts, histograms) of the output data. Document results and conclusions." Maria (1997) also asserts that simulation results are difficult to interpret, even if there are no data collection errors in simulation, the underlying model is fully known, and the replications and configurations are user controlled.

Maria (1997) claims, "An observation may be due to system characteristics or just a random occurrence," and that most types of system data are autocorrelated and not the independent, identically distributed data that most statistical inference techniques assume. Maria (1997) advises use of the performance measures and the run statistics that simulation packages provide, and to use the batch means technique (adjusting total sample size and batch length) to obtain confidence intervals for the mean of autocorrelated data.

After simulation runs, it is useful for a develop to review their stated purpose in creating the model and the desired insights. It is important that any analysis honestly reflect the system which has actually been created in the ABM, rather than the original system which was the inspiration for the model. If discrepancies are found, this is an important starting point for iteration (e.g., make appropriate changes to the experimental design or experimental conditions for runs, and reperform simulation runs).

When incorporating graphical displays of the output data, the researcher should choose displays that communicate the data clearly and in the most meaningful manner possible leveraging effective data visualization techniques. Particularly effective examples in the ABM literature include Vahdati et al. (2019), Berman et al. (2004) and Kuznar and Sedlmeyer (2005). Researchers are encouraged to utilize the extensive body of work on effective data visualization practices (Tufte, 2001).

3.2.11 Recommend Further Course of Action

This section, included at the end of most scientific papers, provides the reader with a summary of what steps can be taken in the future to improve the Agent-Based Model or apply the results generated by the model. In the field of Engineering Design, this typically entails possible addition of features onto the model, a recommendation to conduct some form of human-subjects research to validate the model, etc. Recommending a further course of action allows the authors to share areas of improvement within the model and suggest what research can be conducted in the future based on conclusions made in the paper. Most papers describing Agent-Based Models in the field of Engineering Design include this section to some degree. Some papers dedicate a separate section to this, while others summarize further course of action in the section that concludes the paper. For example, a paper proposing an *Agent-Based Modeling Framework for Simulating Engineering Team Work*, includes a paragraph within the Evaluations and Conclusions section providing recommendations about how future versions of the model could incorporate team leadership to enhance the ABM's realism (Crowder et al., 2012). On the other hand, a study proposing an Agent-Based Model to study the diffusion of alternative fuel vehicles, includes a section called, "Limitations and Future Research." Within this section, the authors of the paper have identified limitations in their model and explained how these gaps could be filled in the future. For instance, the authors identify that their ABM does not consider the relationship between manufacturers and auto dealers and explain how greater complexity could be added to future versions of their proposed model (Zhang et al., 2011). Including a section suggesting further course of action seems to be a well-practiced convention in the field of Engineering Design and is suggested as good practice based on the 11 steps proposed by Maria (1997).

3.2.12 The Future of ABM

The Maria (1997) approach to modeling and simulation provides a systematic approach ABM for simulation in engineering design. Steps *(3) Collect and Process Real Systems Data, (5) Validate Model, and (6) Document Model* are often missing or under-reported in existing agent-based models in engineering design. Effectively incorporating these steps will help ensure quality of the model and model's supporting publications.

Although this chapter is structured according to the steps provided by Maria (1997), it is recommended to treat these steps as a high-level framework and not as a rigid example. There are many ways to approach ABM. For instance, Macy and Willer (2002) also offer a series of recommendations for developing an agent-based model. Firstly, they recommend to *start simple.* Simple models can reveal new theoretical ideas that have broad applicability beyond the stylized models that produced them. Pressure to make models more realistic may result in highly complex frameworks that are difficult to interpret as natural phenomena. Macy and Willer (2002) suggest starting out with a simple model and adding complications iteratively while making sure the dynamics are fully understood before proceeding. They also emphasize the importance of frequent experimentation with careful, systematic mapping of the parameter space. This requires theoretically motivated manipulation of the parameters in the model coupled with a clear statement of hypotheses that guide the experimental design. Finally, Macy and Willer (2002) recommend testing for robustness, external validity, and domain validity. These recommendations ensure that the researcher realizes the rich potential of an ABM approach. ABM can also be approached in an iterative way where the system being studied becomes the altered system which then becomes the system being studied, repeating in a cycle (Maria, 1997).

Though there are different approaches to ABM development, ethical considerations must always be a core component of the development process. The great opportunity inherent in ABM is that it can model various human aspects that are not feasible to measure in the real-world. While this may appear to lessen ethical concerns, the need for model validation (usually against human data) forces developers to contend with aspects of privacy, data sovereignty, protection of vulnerable populations, and other concerns. Rather than being an afterthought, these issues must be central in the development process.

The potential for ABM to enhance our understanding of engineering design through the simulation of human systems is immense. However, to ensure effective model development, execution, and research, there must be resources for researchers new to ABM that help them adopt best practices. This work critically reviews ABM research in engineering design by appealing to

11-step approach outlined by Maria (1997). Three steps are identified as under-reported in the engineering design literature (namely collecting and processing real systems data, validating the model, and documenting the model). Recommendations are offered for best practices across all 11 steps but focus in detail on these three gaps.

The recommendations and utility of the recommendations provided here should be continuously assessed, developed, and refined. As more robust methods and approaches for investigating engineering design are strived after, so too must best practices for employing those methods be reflectively developed.

3.3 NNA PIPER ABM Design Progression

The 11 steps to ABM outlined by Maria (1997) align well, sequentially speaking, with the five main steps of the design thinking process (empathize, define, ideate, prototype, test), a correlation visualized in Figure 3.1 below. While this design process is to be thought of as fluidly iterative, it is commonly accepted that a designer typically begins by empathizing, then defining, etc. This work designing the conceptual model for this thesis follows 11 steps to ABM outlined by Maria (1997) as well as the design process and Sections 4.1-4.3 of this thesis, described below, further discuss these coinciding steps completed as a part of this work.

- Section 4.1: Empathizing with the User
- Section 4.2: Defining the Problem Space
- Section 4.3: Model Dynamics

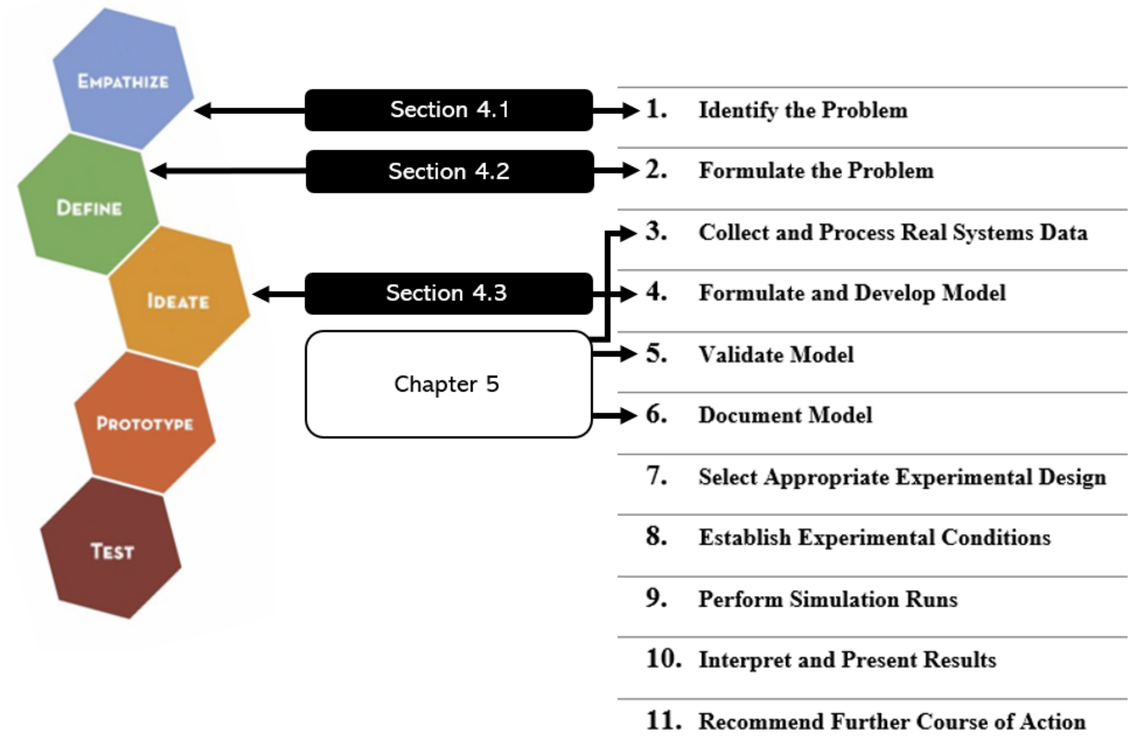

Figure 3.1. Comparison of the design process (left) (Aquino, 2017), thesis sections/chapters (middle), and 11-steps to ABM (right) (Maria, 1997)[10]

Best practices for steps 3, 5, and 6 of the 11 steps to ABM outlined by Maria (1997) are further discussed in chapter 5 of this thesis as a part of future work to be completed by an incoming graduate researcher. Step 3 is also expanded upon in “Limitations.”

[10] Adapted from ASME IDETC Agyemang et al. (2022) and Aquino (2017)

Chapter 4

Conceptual ABM Design Process

This chapter discusses the details of the design process stages followed in development of the NNA PIPER ABM. These steps (empathizing with the user, defining the problem space, and model dynamics) were derived from the comparable steps of (1) the design thinking process and (2) the review of principles for ABM in engineering design discussed in Chapter 3.

4.1 Empathizing with the User

The first step of the human-centered design process is to empathize with the user and gain useful insights into the problems their facing. By identifying these problems, a solution can be designed to resolve them and deliver greater value to the user. In the case of this thesis, the users are government and community decision-makers whose roles influence outcomes of permafrost thaw in the North Slope Borough. This chapter expands upon decision-makers the ABM in this thesis is being designed to serve. Insights from an interview with a government decision-maker and an interview with a community decision-maker are also discussed.

4.1.1 Government and Community Decision-Makers

Human-centered design is leveraged in this thesis to design an ABM, to be used as a decision support tool, for leaders within the four North Slope Borough communities of focus. Complex socio-ecological systems continue to change, and the burden falls on leaders, here referred to as “Government decision-makers” and “Community decision-makers,” to respond.

"Government decision-makers," throughout this thesis, refers to elected officials associated with the United Stated government, which typically would include people in roles at the local, state, and federal levels. This thesis will concern government decision-makers at the local level, since climate change is among the most critical challenges facing local government decision-makers in the north (Birchall & Bonnett, 2019). In Alaska, what might be thought of elsewhere as a "county" is referred to as a "borough," and this thesis focuses on government decision-makers within the North Slope Borough where Point Lay, Wainwright, Utqiaġvik, and Kaktovik are located. Examples of Alaska's borough-level elected leaders include Mayor, Borough Clerk, and Deputy Borough Clerk (North Slope Borough, 2022). The Borough Mayor is empowered to establish and name advisory boards and commissions as needed when they seek to benefit from the advice and counsel of an advisory board comprised of representatives of the citizens they serve (North Slope Borough, 2022).

"Community decision-makers," throughout this thesis, refers to non-elected officials whose community-organizing activities do not directly depend on the United States government authorization to take place. This thesis will focus on community decision-makers whose efforts primarily benefit the North Slope Borough, but also includes community decision-makers whose efforts extend to the North Slope Borough from another location within Alaska. An example of one particularly influential community decision-maker is the Alaskan Federation of Natives, which is the largest statewide Native organization in Alaska (Alaska Federation of Natives, 2021). According to the organization's website, its membership includes 158 federally recognized tribes, 141 village corporations, 10 regional corporations, and 12 regional nonprofit and tribal consortiums that contract and compact to run federal and state programs. AFN is governed by a 38-member board, which is elected by its membership at the annual convention held each October. The mission of Alaska Federation of Natives is to enhance and promote the cultural, economic, and political voice of the entire Alaska Native Community. Leadership within the Alaska Federation of Natives includes a President and two Co-Chairs.

4.1.2 Summary User Needs Based on Stakeholder Interviews

To better understand government and community decision-maker needs, two stakeholders were interviewed. These stakeholders will henceforth be referred to as Interviewee 1 and Interviewee 2 in this thesis. Both stakeholders have certain relevant experiences and insights, discussed below, that have made them a valuable part of designing the conceptual ABM of focus for this thesis. This section, Section 4.1.2, is a summary of insights overcovered in interviews with interviewee 1 and 2, supported by literature.

Interviewee 1 conducts research on human adaptation to environmental change through resilient design. They also use their expertise in social-ecological and technological systems science to develop ways to improve domestic resource security for community well-being, Interviewee 1 has also served as an advisor on advanced data and analysis for the Department of Defense, and in a managerial role within the Department of Homeland Security. Interviewee 1 has over 20 years of experience working with the communities of interest in this study. Because of their experience working closely with Federal agencies, Interviewee 1 is an appropriate government stakeholder.

Interviewee 2 is an anthropologist and archaeologist working and living in the North Slope Borough for many years. They have extensive experience in anthropology in Alaska, including ethnographic research and archaeological site surveys, mitigation, testing, and research at sites throughout Alaska. Interviewee 2 has more than 30 years of experience, specializing in Arctic cultural resource management, community archaeology, and Arctic science support and logistics. Because of Interviewee 2’s long-term residence in the North Slope Borough and their extensive experience working with Iñupiat peoples, they are an appropriate community stakeholder.

The following is a body of knowledge, combined after meeting with Interviewees 1 and 2 on separate occasions, which highlights some of the needs of government and community decision-makers. ***Within this thesis, the core need of decision-makers from which many others are derived is the fulfillment of their government and community leadership roles.*** The remainder of this section highlights specific supporting needs and ties them back to the role of decision-makers as community stewards; key needs are bolded and underlined. The problem space which will guide model design ideation is defined based on these user needs.

Both Interviewees believe government and community decision-makers need to prioritize building greater adaptive capacity and resilience (Alessa & Kliskey, 2021). perhaps **partially by uniting with other Alaskan boroughs. Decision-makers also need to contend with special interests such as oil (Kishigami, 2021), which village corporations make a decent profit from according to Interviewee 2.**

A major task of decision-makers is to ensure communities have access to basic resources. According to Interviewee 2, decision-makers need to pay attention to power supplies, such as the diesel which comes in by barge and is stored in tanks near the coast for simplicity's sake. Interviewee 2 provides an example: if these tanks are to break down after barge season, the community would not have access to oil other than through the very expensive process of having it flown in. Additionally, each year there are less and less animals around to support the community's food needs, as food availability is largely dependent on hunting and fishing (Kishigami, 2021). If infrastructure fails, then it is likely that food and water security will also fail rapidly, according to Interviewee 2, who also states that if water or sewage fails, it will take a very long time to fix it. This is particularly grim considering that energy costs depend on so many factors, and it is well-known that food from stores in the North Slope Borough is astronomically expensive and contributes to food insecurity (North Slope Borough, 2019). **Decision-makers need to**

prioritize meeting community member's basic needs because inevitable infrastructure failure leaves communities vulnerable.

Not only do decision-makers need to defend against insufficient resource access, but they also need to reduce potential risk to communities through preemptive action. For example, Interviewee 2 shared that a large amount of hazardous waste can be found in Kaktovik and is susceptible to damage caused by permafrost thaw and exposure to the elements – however, removing or fortifying the waste is prohibitively expensive. The community is also very dependent on airports that cannot be moved (Soos & Ehrlander, 2019), one being between a pong and the ocean according to Interviewee 2. One risk mitigation effort may be relocating communities, if possible (Piggott-McKellar et al., 2019); Interviewee 2 states decision-makers will need to find suitable locations to move communities even though there are few, if any, options as available land is a part of national parks or people's private subsistence cabins. Even if lands are available, decision-makers need mind established flood hazard areas and not build in them, according to Interviewee 2. It's important that any attempt to relocate be well planned for, since resettlement has shown to have poor natural, social, financial, human, and cultural outcomes (Piggott-McKellar et al., 2019). Decision-makers will need to minimize risks as they can with risk-assessed solutions.

When implementing solutions, decision-makers need to account for and protect culture and cultural heritage. Much of this cultural heritage is sitting beneath infrastructure, according to Interviewee 2, and because of these cultural resources, people do not want to move out of certain areas (Farbotko et al., 2020). Interviewee 2 asserts it would be emotionally difficult for communities to relocate inland to areas where the ocean cannot be seen. Other cultural aspects, including personal identities and traditional ways of life, impact potential solutions. Solutions to ongoing socio-ecological issues in the North Slope Borough need to take the regional culture into account.

Inevitably, when infrastructure is compromised in the North Slope Borough, skilled workers will be needed to repair it just like they are needed elsewhere in Alaska as infrastructure is damaged (Birchall & Bonnett, 2019). The North Slope Borough communities need training for technical jobs such as electrician or carpenter because they are very scarce in the region, according to Interviewee 2, who says many of the youth become educated and do not return, and any expertise from the slope often gets hired to work in Anchorage or Washington D.C. **Decision-makers need to prioritize retention of regional talent, and education of potential talent, if communities are to have the capacity to repair their degrading infrastructure.**

According to Interviewee 1, **decision-makers need a holistic understanding of Alaska's socio-ecological systems and cascading effects (Bahlai, 2021) of permafrost thaw** to help them develop mitigation plans aimed at operations across a range of mission needs. In order support these needs, study of Alaskan infrastructure systems is needs to be studied to gain a better understanding of the relationships and how effects in one location might cascade through the system (Bahlai et al., 2021). Interviewee 1 suggests that how important any piece of infrastructure is to a specific community needs to be identified and used to improve the systems analysis approach. Interviewee 1 also states that the ties between communities also need to be studied, which would weigh the effects that one community might have on others. Decision-makers need to have this knowledge available to them to make the best decisions for the North Slope Borough community.

According to Interviewee 1, trust in data, evidence, and science is engendered, in part, by providing useful materials to consumers before circumstances force a decision. Interviewee 1 also states that when decision-makers become familiar with the direct benefits of fundamental research also become familiar with how they can best support research to improve their own decision-making outcomes. Interviewee 1 states new reliable sources of information to understand how the environment is changing and what the impacts are is needed, however, tools for adaptation planning

(Kettle et al., 2019) which support data-driven policymaking provide decisional guidance even when the exact relationships between systems and subsystems have not yet been elucidated. **Decision-makers need to support the gathering of more data to assess permafrost risk and certainty of the risk (Xiao, 2021).** Any increase in certainty or information is helpful for a decision-maker. Researchers avoid making definitive conclusions in the absence of necessary data, but decision-makers do not have that luxury. Decision-makers need to open the door for ongoing, data-driven dialogues about how they can most appropriately adapt to climate change within their community's own social, geographic, and cultural contexts. As the world changes and our understanding of those changes improves decision-makers will need to look to scientists and researchers for knowledge that can help them make better decisions.

Decision-makers need to seek support from state and Federal governments; however, they need not wait years for the political will and funding needed to embark on needed projects (Xiyue Li, 2020). Community decision-makers need to be empowered to act now with little outside help.

4.2 Defining the Problem Space

4.2.1 Overview

Decision-makers serve their communities to ensure community members' wellbeing, and to do so they require the prior discussed needs to be met. An agent-based model can help satisfy these needs, but social system must be defined. To understand the social system at the base of the model which will be studied to gain key insights, it is necessary to define a problem space which represents the challenges the North Slope Borough is facing. Chapters 1 and 2 of this thesis provided background information on climate-change-induced permafrost thaw, and introduced the environmental changes, infrastructure vulnerabilities, and community demographics within the

North Slope Borough. This chapter, informed by the contents of Chapters 1 and 2 as well as the user needs discussed in Section 4.1, defines the design problem space by breaking down key themes central to challenges the North Slope Borough is facing. It is important and valuable to gather information from others when designing anything for application to the Arctic. Designing models meant to replicate socio-ecological systems requires an in-depth knowledge of community culture and function. Being able to gather this information and synthesize it into a scoped problem at which to target design ideation is essential to both the design thinking and ABM design process.

4.2.2 Social-Ecological Resilience

Social-ecological resilience, in the sense used throughout this work, is defined as "the ability of communities and landscapes to detect physical, social, or economic changes; identify their nature; and respond with retaining core social and physical function" (Alessa et al., 2015; Alessa & Kliskey, 2021). The resilience of North Slope Borough communities Point Lay, Wainwright, Utqiaġvik, and Kaktovik is important to assess and bolster in the face of accelerating climate change and permafrost thaw (Alessa & Kliskey, 2021). Because relocation is not a simple or likely option for reasons previously discussed (Xiyue Li, 2020), adaptation seems the only mode by which communities will stay intact. Adaptation and resilience in the face of extreme environments is a part of Arctic people's culture, but as rates of change accelerate, adaption becomes much more challenging **(Xiao, 2021)**. According to Interviewee 1, both communities and government organizations have low adaptive capacity in the Arctic region, with few tools for adaptation planning. Interviewee 1 asserts that advancements in our collective understanding about how Alaskan communities might be impacted by thawing permafrost, but we still need a more holistic view of changing Arctic communities and how permafrost melt will force community adaptations. The people of the North Slope Borough and the systems that support them are interdependent, and this relationship is important to keep in mind when assessing hazard, threat, risk, vulnerability, and resilience (Alessa & Kliskey, 2021). Resilience is a key theme in the problem space being designing for because ultimately the goal of this work is to help communities affected by permafrost continue to exist well into the future.

4.2.3 Health

Community health, at least for Iñupiat people who make up most of the population, is not currently a major problem based on the results of the 2019 North Slope Borough Economic Profile & Census Report (North Slope Borough, 2019). Half the Iñupiat individuals in Point Lay are reported to be in very good or excellent health (North Slope Borough, 2019). Because the health of most of the population is not of dire concern now, health makes for a valuable a measure of community resilience for this work. If community health is poor, adaptation may be more difficult to achieve (Maslow, 1943; Huang, 2011).

Health is a key theme of the problem space for study of this socio-ecological system because it is associated with both poverty and subsistence. 30.1% of household heads with incomes below the poverty level rate their health as poor or fair while only 16% of Iñupiat household heads with incomes above the poverty level have the same self-assessment (North Slope Borough, 2019). Iñupiat people are in better health than Caucasians or individuals of “other” ethnicities perhaps because of their primary reliance on subsistence for their food source (North Slope Borough, 2019). As subsistence is on the decline, according to the 2019 North Slope Borough Economic Profile & Census Report, diseases such as diabetes are on the rise (North Slope Borough, 2019). Health is a key theme of the problem space also because, according to Huang et al. (2011), “opportunities for planning and implementing public health adaptation are reliant on effective strategies to overcome these constraints and barriers,” and those strategies fall on community leaders to decide.

4.2.4 Food, Energy, Water Nexus

Protecting human health and understanding the food, energy, water nexus is identified as one of the National Science Foundation's grand challenges (National Science Foundation b, n.d.). Food security is certainly a problem in the North Slope Borough, where 96.20% of Iñupiat households use subsistence foods, and 58.30% percent of households in the North Slope Borough community and 71.50% of households in the villages receive half or more of their diet from subsistence foods (North Slope Borough, 2019). However, approximately 36% of Iñupiat households have some form of food insecurity, which is about three times the national average (North Slope Borough, 2019). A quarter of household heads in Point Lay reported not having enough to eat, while a third of household heads in Wainwright reported the same (North Slope Borough, 2019). Utqiaġvik and Kaktovik have proportions of 20% or less of household heads reporting a lack of food, which is still three or four times the national proportion (North Slope Borough, 2019). Subsistence is decreasing, as we see dramatic decreases in whaling activities, harvesting of seals or walrus, and participation in gathering of plants and berries (North Slope Borough, 2019). The decrease in sea mammal hunting has largely been attributed to environmental changes due to climate change (North Slope Borough, 2019), and perhaps as Interviewee 2 mentioned, there just aren't enough animals around anymore to support the community. It is important to consider food security as a major theme in the problem space, especially as we see decrease in subsistence (Kishigami, 2021). Households most dependent on store bought foods are those most worried about obtaining all the subsistence foods they need, and community members may become more dependent on store bought foods into the future given food security trends associated with environmental change (North Slope Borough, 2019). The focus on FEWS with respect to community resilience is supported by Maslow's Hierarchy of Needs (Maslow, 1943). Maslow's Hierarchy of Needs states that human actions are motivated by certain physiological and psychological needs that progress from basic to complex (Maslow, 1943). The hierarchy also suggests that people are motivated to fulfill basic needs before moving onto other, more advanced needs (Maslow, 1943). The base of Maslow's hierarchy addresses physiological needs, as can be seen in Figure 4.1 below. As Maslow's theory states, people need to fulfill each layer before they can fulfill those on top of it. Community adaptation, cultural preservation, and other important objectives fall in the "Safety and Security" level, or higher. In contrast, maintaining secure access to food, energy, and water fall in the physiological needs layer. Therefore, it is paramount that communities manage their physiological needs to power their adaptation capabilities.

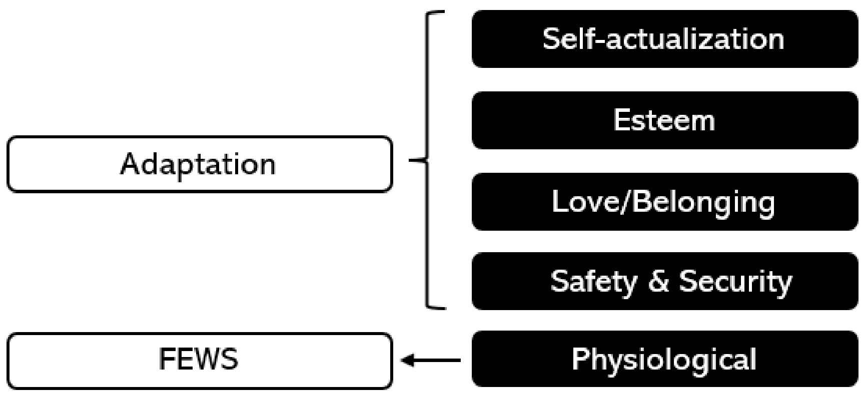

Figure 4.1. Maslow's Hierarchy of Needs

4.2.5 Socioeconomics

According to the findings of the 2019 North Slope Borough Economic Profile & Census Report, household income has almost no impact on an Iñupiat household's dependence on subsistence foods (North Slope Borough, 2019). However, Point Lay experienced decreases in in average subsistence expenditures between 2015 and 2019 (North Slope Borough, 2019). The census also found that half of all households who could not afford to purchase enough food were not working, especially in Utqiaġvik where 70% of the households unable to purchase food were not working (North Slope Borough, 2019). Socioeconomic status of community members is an important theme of the problem space because it is directly related to issues such as food insecurity in the North Slope Borough, such as a lack of income to purchase food, the high cost of food, lack of employment, and the unpredictability of income (North Slope Borough, 2019). Nearly every household in Point Lay and Wainwright cited high cost of foods and the high costs of other bills as the main reason they could not afford to purchase enough food (North Slope Borough, 2019). In Utqiaġvik, 70% of the households unable to purchase food were not working (North Slope Borough, 2019). Social factors such as ethnicity are important to consider regarding resilience of communities, especially when the census reports that Iñupiat households experienced about 72% of the total average household income of Caucasian households (North Slope Borough, 2019). As climate change persists and subsistence rates drop, it is likely that there will be less equitable access to store-bought food supply, which Interviewee 2 and the North Slope Borough Economic Profile & Census Report (North Slope Borough, 2019), have already identified as costly. It is an important part of the problem space to consider whether a community can be resilient when the ethnicity which its population primarily consists of is, in an economic sense, living in poverty, and experiencing high rates of unemployment.

4.2.6 Infrastructure

The availability, condition, and cost of housing across the North Slope Borough has become a primary concern for residents, while overcrowding, housing needs, and utility costs add additional strain (North Slope Borough, 2019). Most of the North Slope Borough population is Iñupiat, and their population is growing; many residents across the North Slope are living in overcrowded or "very overcrowded" housing (North Slope Borough, 2019). Even though non-Iñupiat households account for less than 20% of total housing units on the North Slope, overcrowded housing units among non-Iñupiats is very low or nonexistent in most villages (North

Slope Borough, 2019). Liew et al. (2022) found that housing is reported as the most affected type of infrastructure in the four Arctic coastal communities and is also most reported to have wall cracking house tilting damages (Liew et al., 2022). However, because of the extent of overcrowding in all North Slope communities, construction of new housing and renovation of dilapidated housing has been identified as a likely solution – extending road and power infrastructure to platted residential lots in the process (North Slope Borough, 2019). As more and more housing is needed due to overcrowding, structures will need to be erected in such a manner that they are resilient to permafrost thaw (Alessa & Kliskey, 2021). The circumstance and priority of housing in the North Slope Borough is just one aspect of infrastructure that makes it such an intriguing theme of the problem space.

Surface water ponding, ground surface collapse, and differential ground settlement are the three types of changes in ground surface manifested by permafrost degradation (Liew et al., 2022). Residents of the North Slope Borough reported seeing damages to infrastructure such as residential buildings, roads, buried pipelines, and utilidors, but effects on civil infrastructure seem to vary between communities (Liew et al., 2022). Unfortunately, less than half of the damages to residential buildings seem to be repaired, which validates concerns about capacity for resilience regarding the skill available to complete repair tasks (Liew et al., 2022). FEWS security is threatened if infrastructure breaks down, indicating access to resources is a fragile system (Alessa & Kliskey, 2021). Energy access and associated costs in the North Slope Borough community is just as volatile according to Interviewee 2. North Slope Borough power comes in "from the outside," (Whitney et al., 2019) meaning that diesel, the primary source of heating for housing units (North Slope Borough, 2019), comes in by barge. Storage tanks are usually placed near the coast to simplify fuel transfer processes, but this is potentially catastrophic for the community. Interviewee 2 states, if the tanks break due to an event such as a flood (Buzard et al., 2021) after barge season then fuel would need to be flown in which would be extremely expensive. On a related note, Arctic coastal communities are very dependent on airports (Soos & Ehrlander, 2019) that are affected by permafrost thaw but can’t be relocated in the community, according to Interviewee 2. Overall, the North Slope Borough is very dependent on infrastructure for their basic resources, however, this infrastructure is in harm’s way (Liew et al., 2022). In Kaktovik, Point Lay, and Utqiaġvik the senior population is growing (North Slope Borough, 2019), so dependence on infrastructure may even increase based on the changing needs of this demographic. Because of the risk to resilience-building community health and wellbeing that infrastructural fragility would seem to be, infrastructure is a critical aspect of the problem space.

4.2.7 Cascading Effects

In this work, cascading effects include a wide array of unforeseen chains of event that result from a variety of actions or changes in a system (Bahlai et al., 2021). As has been discussed in the previous sections, permafrost thaw leads to infrastructural damage, which results in FEWS insecurity that is likely to impact community health (Brady & Leichenko, 2020). According to Interviewee 2, cascading effects of permafrost thaw in the North Slope Borough are poorly characterized and limit planning at multiple scales, but the Alaskan infrastructure system can be studied both in parts and in whole to gain a better understanding of the relationships and how effects in one location might cascade throughout the system. It is Interviewee 2’s expert opinion that these findings could be easily incorporated into a model. For decision-makers to enact appropriately timed responses to adverse effects of permafrost thaw on their communities, it would be helpful to understand the role of various infrastructure and what impacts certain infrastructural breakdown will have on communities (Alessa & Kliskey, 2021). Interviewee 2 suggests that ties between communities, or the cascading effects between communities, should also be studied so that it is possible to weigh the effects one community might have on another. **Cascading effects of permafrost thaw are challenging to characterize ((Xiao, 2021), but must be a part of the**

problem space to fulfill the rightful systems analysis approach at the base of this agent-based model.

4.3 Model Dynamics

This section expands upon the ideation, formulation, and development of the conceptual ABM model. The programming structure for the NNA PIPER ABM is outlined, for reference throughout subsequent sections, to demonstrate how design decisions are translated to programming. Also discussed in this section is how statistical testing of model results can lead to resilience insights, and how the model can be used as both a metric and a prompt for solution design.

4.3.1 Overview

The human-centered conceptual ABM designed as a part of thesis is derived to emulate the socio-ecological system present in the North Slope Borough. This is so that the simulations may provide insight into methods of responding to actual issues occurring within said socio-ecological systems. Much of the design of the system which the model is based on then is copied from the North Slope Borough community dynamics, focusing on the problem space defined previously. A high-level description of the system the model is based on is as follows: infrastructure provides community members with access to food, energy, and water resources, but if community members cannot access those resources (for reasons related to financial cost, lack of resources available, or lack of functioning infrastructure to provide the resources), then their health will be impacted. This chapter first discussed the programming structure which is referenced throughout when explaining concept translation to computational modeling. Model dynamics and corresponding design decision-making is covered throughout the remainder of the chapter.

4.3.2 Programming Structure

This agent-based model is designed to include the following program elements: a settings dictionary, setup script, simulation function, history logging, statistical testing of results, and user-implemented interventions (see Figure 4.2 below). This structure has been developed with the programming language, Python, in mind.

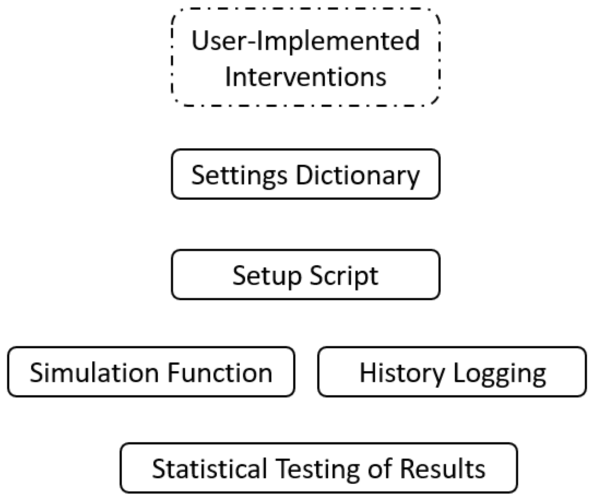

Figure 4.2. ABM programming structure

Settings Dictionary: This theoretical ABM will be constructed with many adjustable parameters which are inputs to the model. The dictionary is an opportunity to intentionally set parameters, such as the number and type of infrastructure entities within the model, as well as parameters like the number of agents. It may be helpful for preliminary versions of the model to rely on the dictionary to explicitly state all parameters.

Setup Script: The setup defines non-time-varying characteristics of agents and infrastructure. Parameters within the ABM that are not explicitly stated but are generated probabilistically from a distribution are defined in setup. For instance, someone gaining insight from the model might want to "roll dice" to implement a random number of agents or infrastructure in the model, and they would do that in setup. Setup is a model class that takes a large input structure that holds many different parameters and has some binary flags (true or false) that indicate the type of scenario to be simulated. Preliminary versions of the model should simply read through the dictionary and create agents and infrastructure.

Simulation Function: Time-varying characteristics of agents and infrastructure are defined in simulation function. Running the simulation allows for all parameters of agents and infrastructure to interact over a certain number of time steps.

History Logging: Agents in every time step are writing their strategy to a log file or CSV as simulation runs; they are recording what happens, as is standard for ABMs. A sub method of the history class is resilience, which contains agent FEWS access data per time step. The history class is where all insights for resilience measurements are stored.

Statistical Testing of Results: Data from model history, parallel sets of resilience metrics, are compared across scenarios. For example, 1000 communities may be randomly generated, ran through the model scenarios, and then their resilience data is calculated in a consistent way. For preliminary versions of the model, running sets and calculating the mean standard deviation will begin to build rigor into the model.

User-Implemented Interventions: External model users can implement interventions in the core model. User-implemented interventions are implemented as a checklist of amendments to the dictionary and set up that adjust the scenario running in the model. The model provides decision-makers the opportunity to assess outcomes, serving as a prompt for solution design.

4.3.3 Design Decision-Making & Translation to Programming

This section expands upon the model dynamics of the ABM, explaining design decisions which led to those dynamics, and how the dynamics will be translated to programming. The design decisions discussed below prioritize parallelism between the model and reality for North Slope

Borough communities. As well, model dynamics have been designed to allow for flexibility, such that this theoretical model can be adjusted to seek insights from a range of varying scenarios.

ABMs operate in terms of time-steps at which every agent in the model can act on its surroundings. For this model, n number and m magnitude of time steps can be defined in the dictionary or randomly generated from a distribution in setup. An appropriate time step magnitude is perhaps seasons or years to capture realistic rates of infrastructure compromise and repair. This design decision is influenced by the time period over which community survey participants observed permafrost thaw effects on civil infrastructure (Liew et al., 2022). Agents and infrastructure in the model are spatially embedded with x-y coordinates, a detail which is implemented in the dictionary of the model or randomly generated from a distribution in setup.

4.3.3.1 Agents

The ABM is a multi-agent model in which only community members are modeled as agents. The only decision-making capabilities of the agents is that which pertains to finding affordable sources of FEWS, if possible. Agents are spatially embedded within the model with x-y coordinates.

The number of agents is implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script, producing list of agents with length *a*. An appropriate number of agents may be in between 100-9000, depending on the North Slope Borough town of focus and desired insights.

Agent home location can be implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script. Each agent is assigned a spatially embedded home location, and some agents may share home locations. The sharing of home locations is representative of families, as households in the North Slope Borough have approximately four family members on average (North Slope Borough, 2019). Sharing of home locations is also representative of the overcrowding within North Slope Borough housing which, as discussed previously, is prevalent (North Slope Borough, 2019).

Currency is spent by community members for access to FEWS within the model. The model accounts for varying socioeconomic status of community members.

Agent socioeconomic status can be implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script. Each agent is associated with a socioeconomic status from a range of socioeconomic statuses within the model based upon the Genie Index which is a measure of wealth concentration in different areas. Socioeconomic status can be associated with values from 1-100 for simplicity. Incorporating agent socioeconomic status is essential especially when studying a society where certain groups differ greatly in income, and some groups are in poverty (North Slope Borough, 2019). Each agent will have an initial wealth associated with it to spend on FEWS, and this amount will be correlated to that agent's socioeconomic status. Initial wealth is implemented as a part of the dictionary or randomly generated from a distribution in setup. Agent wealth replenishment rates for will be executed per time step and will be implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script as well. Each agent is associated with a replenishment rate that is correlated with their socioeconomic status. The replenishment amount could be set to fluctuate to represent inconsistent income in some versions of the model.

The only energy or materials we're focusing on is the flow of are food, energy, and water. The model assumes that these are the primary materials that community members seek out. In addition, no flows of food, energy, or water are modeled to exit the system.

Agent initial amounts of food, energy, and water can be implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script. Each agent will begin with a certain amount of food, energy, and water. Each agent will also be associated with a FEWS quota, an ideal amount of FEWS for their consumption which is also implemented as a part of the dictionary or randomly generated from a distribution in setup. An agent is required to meet its quota and it knows its options for meeting that quota, if it has the currency, are to

1) Spend money

2) Go further afield

3) Spend more time in search

This can be executed in the model with a minimum-maximum algorithm which dictates agents want more resources for less cost. Agents that cannot find FEWS via certain infrastructure will explore their options with other infrastructure, mimicking actual human shopping behavior. When agents exchange currency for FEWS via infrastructure that has FEWS available, the agent's wealth decreases. Agent wealth also decreases as agents spent time acquiring FEWS or travel a distance to acquire FEWS. Time and effort are reduced to monetary cost for simplicity. This resembles actual human systems where travel requires costs in terms of gas in the case of car travel, and time spent may be time away from income earning opportunities. An agent is hardwired to meet its quote and This agent expense can be implemented in the simulation run portion of the programming structure.

4.3.3.2 Infrastructure

The model flows FEWS only via community infrastructure or the infrastructure which travels to the community to deliver FEWS. This defines the community control volume. For purposes of developing this ABM, I have defined "infrastructure" as any artificial, engineered medium that enables access to FEWS. Examples of infrastructure, by this definition are airport landing strips, snowmobiles, grocery stores, etc. A backet for carrying berries is not considered engineered, per this model. The infrastructure in the model will lack identification but will be associated with adjustable characteristics such a spatial embedding, likelihood to compromise, and type of resource(s) it provides. Infrastructure is spatially embedded within the model with x-y coordinates. Environmental effects are not modeled, but infrastructure degradation is. The model can be toggled to degrade infrastructure at rates to replicate corresponding environmental stimuli. When real systems data is included in future work, infrastructure can degrade according to realistic, evidence-based rates.

The number of infrastructures is implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script, producing list of infrastructures with length *i.* An appropriate number of infrastructures will vary depending on desired insights.

Infrastructure location is implemented as a part of the dictionary or randomly generated from a distribution in setup via a list of *i*-locations. Some infrastructures are spatially embedded as housing, or home-zones, for agents and provides amounts of water without travel or time costs. Housing is particularly important infrastructure in the model since it is the type of civil infrastructure most impacted by permafrost thaw (Liew et al., 2022).

Infrastructure type is implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script via a list of *i*-infrastructures. Type refers to whether the infrastructure is associated with amounts of food, energy, and/or water. Some infrastructure in communities, such as a grocery store, provide food and water, which other infrastructure, such as houses, provide water (recall, in the North Slope Borough, running water is available in over 90% of housing units) (North Slope Borough, 2019).

The initial amount of food, energy, and water each infrastructure is implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script via a list of (i×3)-infrastructures. These initial food, energy, and water amounts are correlated with the socio-economic status of agents via the Genie Index.

An infrastructure's price (in the model's unit of currency) of food, energy, and water is implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script via a list of *i*-infrastructures. Pricing of food, energy, and water changes over time depending on supply and demand, and this is accomplished via the simulation function. The varying of price based on supply and demand emulates North Slope Borough economics.

Infrastructure food, energy, and water replenishment is implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script via a list of (i×3)-infrastructures. Infrastructure replenishment amounts can be set to vary over time, and this can be accomplished via the simulation function. The variance of replenishment amounts over time emulates reality and how infrastructure such as grocery stores are stocked in real life. Perhaps replenishment, in some cases, is correlated with demand for food, energy, and/or water at any individual infrastructure. On the other hand, perhaps replenishment isn’t correlated with demand, and as demand for a resource increase, its price increases. These are interesting events to assess via the model.

Infrastructure degradation is implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script via a list of (i×3)-infrastructures. This is an amount of resource (varying in food, energy, and water) which is subtracted from replenishment amounts at any time step. In the model, degradation occurs in varying amounts, emulating the variation in wear and tear on infrastructure in the North Slope Borough. If infrastructure degrades to the point of having zero food, energy, or water, then it is compromised. Infrastructure doesn’t degrade over time but instead compromises suddenly, then it immediately is associated with zero food, energy, and water resources and no agent will be able to acquire food, energy, or water from it. Whether infrastructure compromises due to degradation or sudden-compromise, certain infrastructure can be linked to represent joint-failure. Such a circumstance emulates reality, where compromise of a water treatment plant leads to compromise of the availability of water via the house.

Infrastructure repair is implemented as a part of the settings dictionary or randomly generated from a distribution in the setup script via a list of (i×3)-infrastructures. Infrastructure either (1) does not repair (2) instantly repairs or (3) repairs over time (i.e., it produces more and more resources as it's repairing). To accomplish this, a repair timer is implemented in the simulation function. When the repair timer is not zero, then service level of the infrastructure is zero. Infrastructure, in the model, can be repaired after compromise and re-compromise, emulating the damage and repair of infrastructure located in zones of natural hazard risks.

4.3.4 Model History Logging and Statistical Testing of Results

Community health is measured in the model via comparison of current access to FEWS as compared to the ideal scenario. Small gaps in accessibility will be regarded as impactful on wellbeing, while large gaps in accessibility will be regarded as impacts on health. The model assumes if there is access to FEWS, then they are also quality controlled. The model only focuses on health as it relates to FEWS-access, not air quality, medical supplies, etc.

For this ABM, resilience is considered to be greater when community health is considered adequate or at least not worsening. The assumption being made is that as community health deteriorates, so too does community capacity for adaptation and repair. Assessing community resilience based upon Native and industrial communities' health will aid North Slope Borough decision-makers, and perhaps decision-makers elsewhere in the Arctic, strategize to bolster their communities' resilience.

The model history, as discussed in the programming structure in Section 6.1, is where data from the simulation run is stored. Specifically, the data stored in history keeps track of agents' deficiencies of food, energy, and water throughout all time steps due to lack of wealth. This FEWS access data logged in the history class must undergo statistical testing which will expose resilience insights, and this testing can be done directly in the model.

Ideal FEWS accessibility levels should be determined, based upon national averages. Every agent will have an ideal FEWs consumption per iteration, which will be multiplied by the number of iterations, resulting in the agent's ideal FEWs accessibility. Knowing the ideal accessibility for agents in the model allows for measurement between ideal accessibility and actual accessibility according to the model history data. After measuring these distances, their sum is to be squared. By squaring the distances, smaller deviations from the ideal case don't count for much or have a large impact. If we accept the assertion that health is decreased when there are large gaps of accessibility, then squaring the distances differentiates different cases in terms of community health. In other words, small deviations from the ideal case account for decrease in wellbeing, while large deviations from the ideal case account for decrease in health. This can be executed with a linear Ross function.

Graphing the ideal accessibility over time for food, energy, or water would produce a rectangle, a linear slope, as seen in part (a) of Figure 4.3 below. Part (b) of Figure 4.3 below represents a time varying non-ideal case of FEWS consumption, where the ideal case is not met. The area under the rectangle in figure b would be subtracted from the area under the curve in figure a to determine the deviation in FEWs accessibility. To obtain a measure of efficiency, one must calculate FEWs accessibility relative to the ideal case across many iterations.

$$\eta = \frac{\int A \, dt}{A_{max} \times T}$$

Where A is the variable accessibility to a given resource (one of food, energy, or water), t represents time, A_{max} is the maximum accessibility in the ideal case, and T is the length of time over which the assessment is performed.

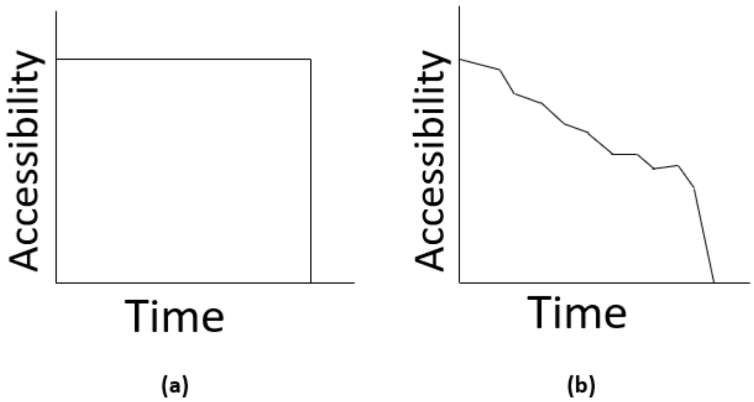

Figure 4.3. Time-dependent FEWS-accessibility per (a) ideal scenario and (b) non-ideal scenario

Agent FEWs accessibility statistics create larger trends which the external user can track to understand trends in community resilience in response to permafrost thaw or other detrimental environmental effects. Community health over time, in a resilient community, would be depicted as a convex sloping curve ((a) in Figure 4.4 below). Regarding a less resilience community, community health would be depicted as a steeper sloping curve ((b) in Figure 4.4 below).

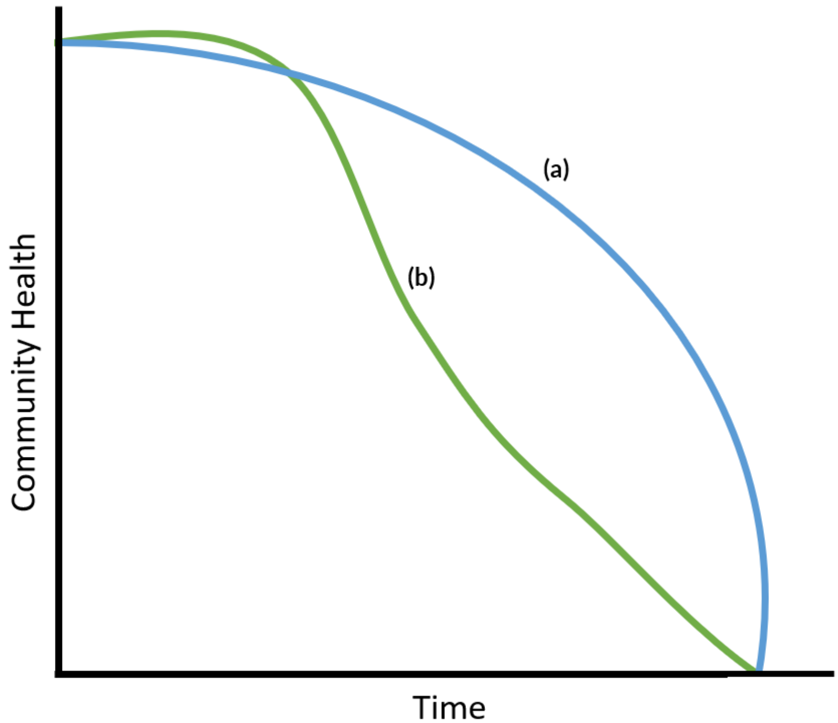

Figure 4.4. Time-dependent FEWS-accessibility per (a) resilient community and (b) less resilient community

4.3.5 Implementing Solutions

Initial insights can be gathered from the model by adjusting the model to observe trends; perhaps those trends catalyzed by environmental changes which are known to lead to specific infrastructural degradation. However, the ABM serves as a useful tool for decision-makers by serving as both a prompt and metric. The external user can make targeted changes to the core model via "user-implemented interventions" such as updating the dictionary or alternating parameters. The external user, or decision-maker, can experiment to determine which scenarios results in desirable outcomes and "work backwards" to turn that model's parameters into metrics for solution design or curation. The decision making would then determine whether they have the time and resources to execute those modifications within their communities. Additionally, the external user can alter the model to represent the changes that the interventions of certain solutions would entail and run the model to assess their impact. Simulation modeling is an excellent tool with which to ideate and test solutions since there are no "real-life" risks in doing so; strategies can be tested within the model and developed outside of the model. Decision-makers have an abundance of solution ideas at their disposal with which to test in the model. Some residents of the North Slope Borough participated in a survey in which respondents were asked what information would be helpful for them to plan for the future in the events of continued permafrost degradation and coastal erosion: (1) what are the effects of climate change on the community, and (2) what should be done? (Liew et al., 2022). Important information, according to survey participants, for planning for the future is categorized into five aspects: (1) natural environment, (2) built environment, (3) cultural awareness, (4) education and communication, and (5) policy (Liew et al., 2022). Some examples of solutions from respondents which could be testing in the ABM include:

- Emergency shelters in subsistence areas
- Stabilization methods for structures and utility services
- Community and critical structure relocation
- Permanent and effective coastal erosion control structures
- Solutions to prevent roads from being washed out by erosion and storm surge
- Frequent maintenance and repair

Chapter 5

Conclusion

5.1 Summary

While a significant amount of research has been conducted over the past three decades, there remain significant challenges to ensuring resilience across local, regional, and national scales. Achieving such resiliency requires an adaptive and innovative approach to address the challenges facing the Arctic, one that engages the co-production of knowledge as well as modern computational tools. Currently, field research remains a focus of Arctic research, leading to both tangible and intangible burdens on often resource-limited remote villages and communities. These burdens are shared by researchers and funding agencies who must spend a disproportionate amount of effort and fiscal resources to support these activities. Field research is infeasible in the age of COVID-19, and the future of field research must also be reevaluated, as it is unlikely that we will return to a pre-COVID-19 baseline. Agent-Based Modeling (ABM) is a computational simulation method that is part of the broader suite of Artificial Intelligence and Machine Learning methods. On its own, ABM could alleviate many of the burdens placed on both researchers and remote communities in situ, enable a wider set of inputs from more diverse stakeholders, and provide more precise guidance to decision and policy makers through the use of futures forecasting. The use of ABM has several benefits, including (1) the mitigation of contentious issues surrounding field work in and near Indigenous communities, (2) better leveraging data collected to date to enable a smaller and more intentional version of field research, and (3) generating a range of scenarios to not only test hypotheses but also explore the outcomes of different policy and intervention decisions.

Focusing field work in this way may help to protect Arctic communities while helping to advance science and more rapidly empower appropriate policy responses.

Adaptation may be the only option for northern Alaskan communities for which relocation isn't an option as climate change accelerates permafrost thaw in the Arctic. Community food, energy, and water security is at risk in the North Slope Borough yet is essential to bolster resilience. North Slope Borough decision-makers require decision support tools that provide a holistic approach to their socio-ecological system. This work details an ABM which provides a holistic approach and accounts for cascading effects of permafrost thaw and the relationship between people and infrastructure. The ABM enables decision-makers to (1) prioritize which infrastructure are most critical to sustain communities and (2) design solutions that can tolerate the complexity of their socio-ecological system. User interviews were conducted to understand the needs of government and community decision-makers, and those user needs were met through the design of this conceptual ABM. As discussed above, a holistic understanding of the North Slope Borough's socio-ecological system and cascading effects of permafrost thaw is the primary need of decision-makers, which this work satisfies. By providing a model that serves as prompt and metric for solution design to bolster FEWS security via infrastructural management, this work also fulfills the need to prioritize greater adaptive capacity and resilience. As well, the process of bolstering FEWS security satisfies the users' need to ensure community access to basic resources. The forecasting nature of simulation modeling provides decision-makers with a much-needed method of reducing potential risk to communities by inspiring preemptive action. While food, energy, and water security the model should aid community capacity for repair, informed targeting of efforts toward critical infrastructure may inspire skilled craftsman intervention which is needed. The ABM helps put much needed power in the hands of government and community decision-makers as they contend with special interests. Protecting culture and cultural heritage is a great need, as people whose histories with the region are extensive could not fathom relocating. By using tools meant to aid their adaptation, communities might be able to stay where they have been for thousands of years. Through use of this model, decision-makers fulfill the needs to support the gathering of data to assess permafrost risk and to act now with little outside help.

5.2 Limitations

This thesis research has been conducted beginning in fall 2020 and commencing in summer 2022. Hence, it occurred during a global pandemic which created great complication and limitation regarding contact with northern Alaskan communities while taking courses at Penn State. Travel to the communities being studied as a part of this research was not justifiable and without this travel, it can be very difficult to understand various community dynamics and each community's infrastructural systems. Though ABM should be leveraged to study communities when contact cannot be made in-person, the pandemic engendered challenges that resulted in the inability to contact local community members even through remote communication. The ideal time to have engaged community leaders would have been during 2020-2021. However, at that time, community leaders were shepherding their communities through the pandemic, and it was potentially detrimental to public health to disturb them or take up their time. Therefore, it was most viable to consult with qualified NNA PIPER specialists rather than North Slope Borough community members themselves.

Real systems data not having been integrated into the model design, even at the conceptual stage, is another limitation to this work. Because of these, the current model design is entirely theoretical and non-specific to the four communities in the North Slope Borough. Real systems data is surely available, but there are barriers to acquiring it which disincentivize its use. Defining desired insights from the model and analyzing which input data will help gain those insights may seem straight forward, but various data sources may need to be accessed to create the bank of data desired. It also may be logistically difficult to piecemeal this data together. The NNA PIPER team this work is completed in collaboration with is interdisciplinary, consisting of engineers, geoscientists, and social scientists. In turn, the modeling work detailed in this thesis was also interdisciplinary, entailing the synthesis and integration of data collected by specialists in various fields. Interdisciplinary fields in general will have a need for data but will not have it at their fingertips; they will not have direct control over the timeline of collection nor direct control over availability of data in adjacent fields. Thus, this is a more general challenge that will require concerted effort to address in the broader scientific community.

The FAIR Guiding Principles for scientific data management and stewardship are intended to improve the findability, accessibility, interoperability, and reuse of digital assets (Wilkinson et al., 2016). According to these guidelines, data should be easy to find for both humans and computers (Findable), and the user of the data should know how to access the data once it is found (Accessible). Both expecting FAIR Guiding Principles to be practiced and practicing them oneself is derived from privilege in that a person or entity must have the resources and abilities to do either. While it is ideal to abide by these guidelines and to use data made available in accordance with these guideline, cumbersome integration of real systems data remains a limitation, especially for groups who are limited in resources. Future work, as it is detailed below, will begin to explore the inclusion of real systems data as it is provided by the broader NNA PIPER team.

5.3 Future Work (Short-Term)

5.3.1 Integrating Real Systems Data

Transfer to program strategy will take place prior to the end of my graduating semester. One of the limitations of my thesis research, as stated above, is the lack of incorporation of real systems data to incorporate into the model design. Therefore, step three of Maria's 11 steps to ABM process (Maria, 1997) was skipped and a theoretical model design emerged. Moving forward, however, it is essential to incorporate the real systems data into the model design and construction. Future work will gather this real systems data from the broader research group contributing to this five-year NSF project, NNA PIPER. NNA PIPER consists of anthropologists, geophysicists, and civil engineers who have spent the past three years collecting data for use in the culminating ABM. Collecting and processing real systems data is the third step of Maria's 11 steps to ABM (Maria, 1997) and is discussed further in prior chapters regarding best practices. Other authors and I found that step three was one of the underreported steps of ABMs, as shown in Chapter 3. The incorporation of real systems data might be complicated to execute and even more difficult to discuss, as information on and acquisition of this data might be dependent on its availability from outside sources. Prior to implementing the data available into the model design, the specific data available might call for adjustments to the existing theoretical, conceptual model to gather desired insights.

5.3.2 Next Steps for the NNA PIPER ABM

After the collection and processing of real systems data, the next steps according to Maria (1997) are to validate and then document the model. Both are underreported steps in the design literature, as shown in Chapter 3. Validation of an ABM may be difficult, however, because stakeholder intervention is required, and this can be an involved process. For example, the ABM in development for this thesis would need to be validated by members of the North Slope Borough community. A variety of methods may be employed, including stakeholder workshops, phone call interviews, and other viable communication methods used to conduct various stakeholder interventions. Game design may be used for each stage of the participatory modeling process to aid learning, communication, and engagement since gamification has been suggested to have a high potential for improving the quality of the participatory modeling process (Bakhanova et al., 2020). Bakhavova et al. (2020) highlight additional research that is needed for designing particularly practical gamified applications in a participatory modeling context. Regardless of which method is chosen, care should be taken to avoid the key research and practices issues for participatory modeling which Hedelin et al. (2021) have outlined for improving participatory modeling as an approach for real-world participatory planning and governance. Engaging stakeholders in workshops, phone calls, or gamified activities facilitate a multi-value perspective and can be closely tied to democratic process, which in a user experience design sense is the process of actively involving all stakeholders (e.g., citizens, users, partners) to help ensure that the result meets their needs and is usable (Hartson & Pyla, 2018). A multi-value perspective and a process which integrates across organizations within a governance system, that which participatory modeling is (Hedelin et al., 2021), are essential in the Arctic where stakeholders (e.g., tribes, communities, industry, military) of this socio-ecological system are impacted at varying scales.

To validate a model representing a human-centered system, the humans of that system must be engaged with several workshops to validate the model. The first stakeholder workshop is the most crucial, as this is where the most information will be gained regarding feedback on the model's accurate representation of the human-centered system. Workshops thereafter will be for the purpose of refining the model and gathering targeted feedback on specific aspects of the model to increase system accuracy.

Regarding the documentation of the model, which is also an underreported step of Maria's 11 steps to ABM, any programming should be made readily available through GitHub or a similar service, and it should also be well-commented and explained. Those who read model documentation should be able to accurately understand this base-system to better navigate any code attached to the project.

5.4 Future Work (Long-Term): More Opportunities for ABM in the Arctic

Looking ahead at how further research might be conducted in the North Slope Borough communities to help address issues arising from permafrost thaw and other socio-ecological change, there is opportunity for further use of modeling methodologies to assess community resilience and aid community decision-makers. Not only can these models be applied to permafrost thaw, but the many other socio-ecological elements such as the melting of sea ice and migration of wildlife as they impact local human-centered FEWs systems. As more data is gathered throughout the change of Arctic systems, better models will be able to be constructed as they will be able to reflect ongoing trends more accurately. Much of the challenge of decision-making today is that the natural world is changing at such a rapid pace that much of the effects we're seeing are unprecedented. At this point, the world is experiencing change at such a rate that Indigenous knowledge of ecological trends and corresponding adaptations are becoming less reliable. It is difficult to know and model systems for which we have not distinguished patterns and relationships. As we unfortunately experience and therefore understand better the effects of permafrost thaw and other climate change effects, there will be more opportunity to apply ABM methodologies.

To help community decision-makers regardless of where communities are located, decision-making aids designed with a user-centered focus should be further developed. These tools could be particularly helpful for decision-makers of smaller communities without an abundance of insight and resources to guide their response to community stressors. Smaller communities can likely become more resilient if we are able to help them anticipate trends and identify societal weaknesses which make them more vulnerable to harsh change. ABMs, when designed with the end-user in mind (includes a GUI, is simple to use, accompanied by training, etc.), could be helpful for small-community leaders to keep their communities safe as the world undergoes climate change.

Chapter 6

Epilogue

I had not been involved with research in any meaningful capacity throughout my experience as an undergraduate, as I anticipated my role to be in industry. Upon discovering "late in the game" that graduate school would be the path best fit for me, I realized there would be much I'd need to learn if I were to be successful in academia. Over the course of the past two years during which I've been completing my Engineering Design master's program, I have learned a great deal not only regarding my research topic, but especially how research is conducted. I'm grateful for the bodies of knowledge I've gained insight into and skills I've begun to hone. Below are a few key takeaways from my experience conducting my master's thesis research.

To design the ABM which would simulate the human-centered systems of the four communities in the North Slope Borough, Alaska, I conducted a preliminary literature review. Through this review, I gained a deep understanding of the Arctic socio-ecological systems and, more specifically, how Arctic human populations (both Native and industrial) are responding to environmental stressors as climate change subsists. This is of particular importance to my professional journey as I intend to pursue further study of human-centered systems using modeling techniques. My next research endeavors will again partner with Arctic communities navigating their options as the world continues to transform. Throughout my master's program, however, I have learned the importance of understanding the problems and experiences of the "user" before developing solutions. As such, having documented the knowledge I've gained regarding the socio-ecological systems of the four Alaskan communities central to this project is paramount for further model development, and therefore solution development, which is discussed in more detail below.

Beyond study of socio-ecological systems as they exist, I gained crucial experience designing social systems as they would exist in my ABM. Not all elements of a system must be included in a model to gain desired insights; only those elements which are discovered to impact those desired insights should be included. Once desired insights and related elements were determined, I learned to organize them into the basic system upon which my ABM would operate. The experience I gained did not stop there, as I would then begin to transfer the conceptual social system knowledge I'd organized into Python, strategizing how I would accurately program the social system and the changes it would undergo to gain the desired insights. Having practiced systems design and system transfer, I will be especially prepared for further research pursuits within the field of Systems Engineering which will require these skill sets.

I'd previously stated that I did not have any meaningful prior research experience before beginning my master's, and the same could be said for my experience with simulation modeling. When I was first introduced to ABM, I was not aware of the knowledge that simulation modeling could contribute, especially applied to key circumstances such as those regarding the resilience of northern Alaskan communities. I feel as though I have become a better researcher and have challenged myself to try new techniques and approaches to the design of the systems central to this research. Throughout my work on this thesis, I've been challenged me to try new techniques and approaches regarding my writing, my presentations, and my communication strategies which have been advantageous beyond use for research. The greater lesson I've learned through the successful use of these techniques and approaches that were new to me is that, as a designer, it is advantageous and perhaps even life-changing to open one's mind to alternative ways of doing things that, once mastered, can cause one to be more effective. Therefore, whether it's knowledge of a particular subject area, methodologies, or personal technique, I feel I have gained a highly valuable master's thesis experience.

Beginning August of 2022, I will be enrolled in the Cornell (Social) Systems Engineering program and will be researching the power dynamics within standard data science practices and specifically how they impact marginalized communities. I will be partnering specifically with Indigenous communities to complete this research and gain valuable insights which I will then return to those communities. My methodologies will potentially include systems dynamics modeling, agent-based modeling, and policy modeling where appropriate. I will also be acquiring minors in both American Indian and Indigenous Peoples Studies and Demography/Human Ecology which has a strong policy-analysis and management focus. My passion for the subject areas and methods I will study as a part of my Ph.D. research is derived from my work completing this master's thesis. Through this work, I've discovered my interest in modeling human-centered systems and communities to analyze various aspects of wellbeing and resilience. Specifically, I've enjoyed analyzing how wellbeing and resilience can be impacted by infrastructure. Using the definition of infrastructure as it has been defined prior, "anything engineering," then the data science systems I will be studying apply. Modeling both quantitatively and qualitatively will provide me with a way to trace hard-to-trace resources, such as data and power, through communities.

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