DYNAMIC MODELING OF ARCTIC RESOURCE ALLOCATION FOR OIL SPILL RESPONSE

By

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ABSTRACT

A mixed-integer linear program is proposed to model the dynamic network expansion problem of improving oil spill response capabilities to support energy exploration in the Arctic. Oil spill response operations in this region can be hampered by a lack of existing infrastructure, limited pre-positioned response equipment, and the possibility that response equipment might not arrive in time to mitigate the impact of a spill because of distance and infrastructure limitations. These considerations are modeled by two inter-related constraint sets with the objective of minimized total weighted response time for a set of potential oil spill incidents. One constraint set determines how to dynamically allocate response equipment and improve the infrastructures necessary to stockpile them within a network of response sites. The other set determines how to utilize this stockpile to respond to each task necessary for an incident by scheduling the equipment to complete tasks. These task completion times are subject to deadlines which, if not met, can, instead, require costlier follow-on tasks to be scheduled. The model, its assumptions, and data requirements were assessed by subject matter experts in the United States (U.S.) Coast Guard and a major Oil Spill Response Organization in the context of oil spill response logistics to support energy exploration initiatives in the U.S. Arctic.

1. INTRODUCTION

Planning, prevention, and response activities for sudden-onset extreme events are challenging, and consume large portions of federal, state, and municipal budgets and time; in FY2014, the United States (U.S.) Department of Homeland Security alone allocated $13.45 billion for these activities (U.S. Department of Homeland Security, 2013). In this thesis, the focus is on oil spill response in the U.S. Arctic. Energy exploration and growing maritime activity due to increasingly ice-free navigational waters have led to concerns over the region's capability to manage a major oil spill disaster (Papp, 2013; National Academy of Sciences, 2014). A mixed integer linear program is proposed to address the unique challenges of oil spill response in the U.S. Arctic and similar remote regions; this model provides decision-makers with new computational tools that examine how the dynamics of pre-staging equipment and improving response site infrastructures impact incident response times. This is believed to be the first model to incorporate the consequences of missed deadlines in terms of needing to complete a different task to mitigate the impact of the missed deadline.

The Beaufort and Chukchi Seas in the Alaskan Arctic are estimated to contain a combined 90 billion barrels of oil, 1,670 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids, in total accounting for 22% of the world's undiscovered and recoverable energy resources (Bird et al., 2008). Economic incentives to recover these resources have led to significantly increased maritime traffic and the potential for seasonal offshore drilling to occur, spurring interest in examining resource allocation challenges pertaining to the region's oil spill response capability (National Academy of Sciences, 2014; Huntington et al., 2015; National Petroleum Council, 2015). Issues concerning the lack of deepwater ports, few roads, and limited air and maritime navigational infrastructure, combined with few potential storage locations and extreme seasonal environmental conditions, complicate these challenges, including the supply, access, and deployment of emergency response equipment (Brigham, 2010; National Academy of Sciences, 2014). Figure 1.1 (National Academy of Sciences, 2014) shows the offshore energy exploration, planning, and development areas in the Arctic relative to the small number of sparsely populated villages in which Arctic oil spill response infrastructure resides. Resource allocation challenges associated with a large oil spill incident from vessel spills and oil drilling operations are of concern to Arctic decision-makers (U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region, 2011a, 2011b; United States Coast Guard, 2013). Arctic oil spill response requires the deployment of oil spill response equipment, or *resources*, such as oil absorbent boom, skimmers, and maritime vessels, in order to complete *tasks*, the pieces of

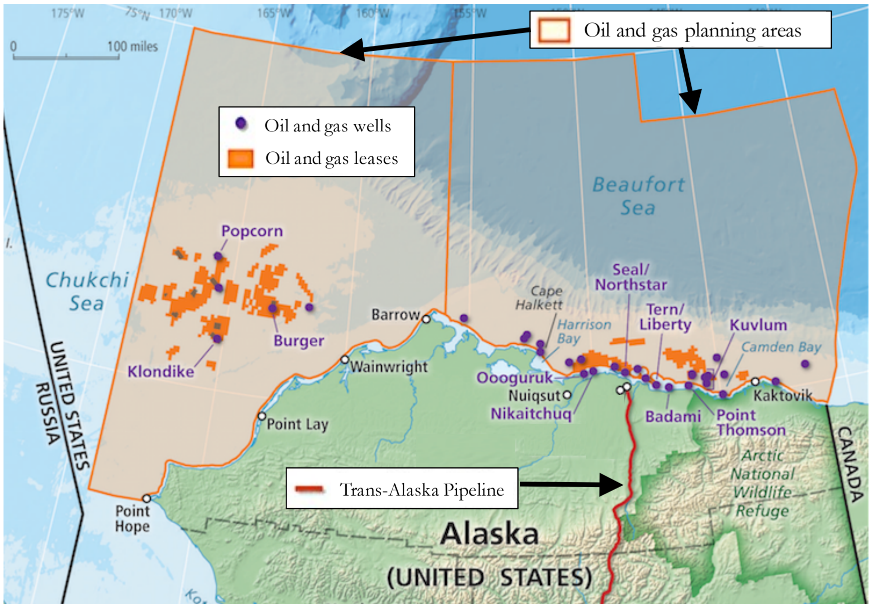

Figure 1.1: Oil and gas wells, leases, and planning areas in northernmost Alaska (National Academy of Sciences, 2014).

work necessary to restore an affected region to normalcy (Alaska Clean Seas, 2012, 2013). However, any planned response is often reliant on private industry resources under current oil spill contingency plans (U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region, 2011a, 2011b; Hamilton, White, Lammers, & Myerchin, 2012; Alaska Clean Seas, 2012, 2013). Arctic decision-makers are concerned with how to stockpile these resources and improve the infrastructure in Arctic communities; how these stockpiles influence resource deployments and improve spill response; and how these decisions help ensure an effective response.

The oil spill *response sites*, formed by Alaskan communities that stockpile resources within their infrastructure and mobilize them to complete tasks during a response, are modeled as a network. Resource allocation models for networks of Arctic response sites must address challenges regarding seasonality, location, scale, and scope. Decision-makers are interested in four key concerns related to these challenges: (i) reliance on a few remote response sites to mobilize resources for deployment at a potential spill incident; (ii) dynamics involving fluctuations in resource stockpiles; (iii) lack of sufficient mobilization capacity at each response site (e.g., a site's ability to prepare resources for transit to the spill incident), and task completion capacity at each incident location (e.g., the ability to concurrently complete tasks at an incident); and (iv) limited budgets to build infrastructure to store response resources (e.g., booms, skimmers, vessels, etc.). These concerns motivate the case study (CS) questions, which influence the model's formulation and focus the computational tests and sensitivity analyzes of the case study:

CS1: What are the impacts on response times of budgetary limitations?

CS2: How does geographic position within the response network influence the scale and scope of a stockpile?

CS3: What is the optimal stockpile improvement policy?

CS4: What is the optimal infrastructure investment policies?

CS5: How do bottlenecks and delayed resource deployments impact the solution?

CS6: What are optimal task completion policies?

CS7: How does the inclusion of additional response sites impact the solution?

The remainder of this thesis is as follows. Chapter 2 describes previous work to develop related models for oil spill response, and the limitations and challenges of applying this earlier work to the Arctic. Chapter 3 introduces terminology, describes the model, and provides tables of notation. Chapter 4 discusses the method to generate test instances from a realistic case study of the Arctic, considers the computational difficulty of these tests, and presents their results. Chapter 5 presents conclusions derived from the analysis of test instances in the previous chapter, and suggests directions for future work. The Appendix provides additional assumptions along with the complete model.

2. LITERATURE REVIEW

Prior work has examined resource allocation in the context of oil spill response using goal-, mixed-integer-, and stochastic-programming, as well as econometric models. This work has assumed that response resources can be sited in proximity to an incident, such that the assumption of an adequate on-time response is valid. Charnes, Cooper, Harrald, Karwan, and Wallace (1976); Charnes, Cooper, Karwan, and Wallace (1979) conducted work that developed goal-programming models for U.S. Coast Guard resource allocation decisions for marine environment protection and evaluated resource type planning policies for marine pollution disasters. Belardo et al. (1984) developed a multiobjective set-covering model for evaluating response resource siting policies that focused on minimizing the probability of potential oil spill occurrence. Psaraftis et al. (1986) developed a mixed-integer programming resource allocation model for oil spill incident response that focused on building facilities to hold response resources and then acquiring appropriate equipment for response. Srinivasa & Wilhelm (1997) developed a multiperiod integer program for oil spill response resource allocation that measures response time by the total minimized time required to respond. Iakovou et al. (1997) developed a non-dynamic, deterministic integer-programming model for oil spill response resource allocation that selects the optimal number of facility sites, amount and type of material, and dispatching policies. Gawande & Wheeler (1999) modeled the statistical expectation of response time of the U.S. Coast Guard Maritime Safety Program by way of probit- and Poisson-based econometric models. Verma et al. (2013) extended the work of Psaraftis et al. (1986) and Iakovou et al. (1997) by developing a two-stage stage stochastic model that pre-positions response equipment to meet uncertainty in spill occurrence and characteristics.

Previous work (e.g., Psaraftis et al. (1986); Srinivasa and Wilhelm (1997); Iakovou et al. (1997); Verma et al. (2013)), while methodologically similar to ours, does not account for resource allocation for remote incident response networks such as those in the Arctic. Earlier work assumed that there was at least one site that could send resources to a particular oil spill incident within a critical time window. However, this assumption does not hold for remote response networks, where resources are potentially subject to significantly long transit times. Prior work typically assumed the response network was sufficiently capable and ignored the consequences of an insufficient response, which is more likely to occur in remote and infrastructure-limited networks. Dynamics concerning the configuration of *resource stockpiles*, the number and type of resources on-hand at all sites within the response network, were assumed to be insignificant. Certain remote regions face environmental conditions that can prohibit actions during one or more seasons and necessarily limit stockpile reconfiguration decisions at those times. These regions therefore must incorporate seasonal dynamics into the decision making process. Finally, much of the prior research focused on minimizing costs incurred during a response effort instead of increasing response capabilities subject to budgetary limitations in order to minimize response times. Resource allocation is addressed differently from Psaraftis et al. (1986) given the dynamic nature of the decisions, and the potential to begin by introducing a particular capability via infrastructure construction decisions. The possibility of resource stockpile reconfigurations in response to seasonal changes is also considered, thus improving applicability of the work to the Arctic problem. The oil spill response constraints are distinct from those found in Iakovou et al. (1997) and Verma et al. (2013) in order to enable examination of the consequences due to insufficient capability resulting from remote and infrastructure-limited response networks. A mixed-integer linear program is developed that supports dynamic resource allocation and network improvement decisions in remote regions and considers the impacts of failing to adequately respond, leveraging earlier work in oil spill modeling by (Charnes et al., 1976, 1979), maritime risk (Van Dorp, Merrick, Harrald, Mazzuchi, & Grabowski, 2001; Merrick et al., 2000; Grabowski, You, Song, Wang., & Merrick, 2010), and recent analysis in dynamic network restoration and expansion (Romeijn, Sharkey, Shen, & Zhang, 2010; Sharkey, Geunes, Romeijn, & Shen, 2011; Nurre, Cavdaroglu, Mitchell, Sharkey, & Wallace, 2012; Averbakh, 2012; Averbakh & Pereira, 2012; Cavdaroglu, Hammel, Mitchell, Sharkey, & Wallace, 2013; Qiu & Sharkey, 2013; Nurre & Sharkey, 2014; Baxter, Elgindy, Ernst, Kalinowski, & Savelsbergh, 2014; Forbes, 2015; Kalinowski, Matsypura, & Savelsbergh, 2015; Averbakh & Pereira, 2015). This approach is applied to the case of oil spill response in the Alaskan Arctic, a region which demonstrates the criticality of the aforementioned assumptions.

3. A MIXED-INTEGER PROGRAMMING MODEL FOR IMPROVING OIL SPILL RESPONSE CAPABILITIES IN REMOTE REGIONS

In this chapter, the model is described by introducing relevant terminology and notation. The mathematical formulation is presented in the sections to follow. Set definitions are presented in Table 3.1, variable definitions are presented in Table 3.2, and parameter definitions are presented in Table 3.3. A mixed-integer linear program is formulated by two inter-related constraint sets to address the resource allocation challenges faced by an Arctic oil spill response network: *the resource allocation component* and *the oil spill response component.* The two components work together to allocate resources dynamically throughout a network of response sites to create "stockpiles" and then provide the weighted response times generated by using those stockpiles to respond to a set of potential oil spill incidents. The resource allocation component modifies the stockpile configuration across a *resource allocation time horizon.* Stockpile configuration decisions for each potential incident improve the response produced by the oil spill response component. The oil spill response component produces a *task schedule* by minimizing the weighted response times of completing all necessary tasks across a *incident response time horizon*, subject to the resources required and their deployment times and positions within the stockpiles of the response network. The objective of best possible weighted response times is considered for each of the potential incidents occurring in one or more time periods of the resource allocation time horizon. The model was vetted with subject matter experts in Arctic oil spill response in the U.S. Coast Guard and in a key oil spill response organization operating in the region; we discuss how this vetting process impacted the model's development in Section 3.5.

The oil spill response component models the decisions necessary to complete the tasks for each potential incident response by utilizing resources stockpiled within one or more response sites. Figure 3.1 illustrates the timeline of activities for a resource of type i located at site j to be used in response to incident e. First, the resource is *mobilized* at site j, whereby the resource is prepared for transport to the incident location. Then, the resource spends time in transit from site j to the incident location. Next, the resource is *deployed* for use with the task, and the point in time when this process has finished is considered as the resource's *deployment time.* Last, the task is *completed*, whereby all resources it requires have been deployed and the task's activity may commence. The point in time when this process has finished is considered as the task's *completion time*, which is equivalent to the resource's deployment time for tasks requiring a single resource. For a particular incident, the total weighted response time is the sum of the product of the task completion times and their weights.

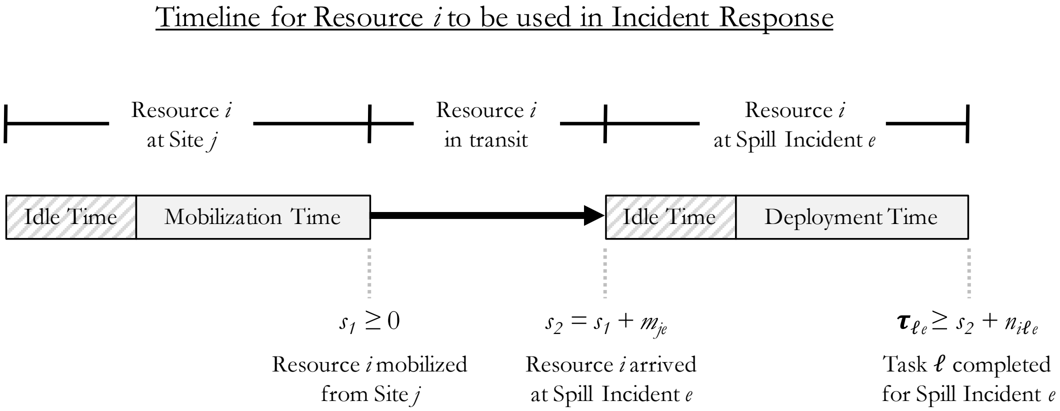

Figure 3.1: The timeline of activities for resource i to be used for task ℓ in response to incident e. Time s_1: resource i has been mobilized for transport to incident e from response site j, and idle time can be introduced by the mobilization capacity of site j. Time s_2: resource i has arrived at the spill incident after the time required to transport it from the response site (m_{je}). Time s_3: task ℓ is completed ($\tau_{\ell e}$) after the time required to deploy resource i for the task at the incident ($n_{i\ell e}$). Here, idle time can be introduced (i) if time was spent waiting for other resources to arrive, (ii) due to the capacities at the incident site, or (iii) due to the time spent completing the safety task. Notes: (a) a resource's mobilization time is assumed to equal one for all resources; (b) the task's completion time is equivalent to the resource's deployment time for tasks requiring a single resource.

The completion time of a task depends on the time required to transport and deploy the resources arriving from one (or more) response sites, and on certain factors which can cause delays or bottlenecks. These factors include: (i) *resource mobilization capacity*, the number of resources which can be mobilized at a response site for transport to an incident location per time period; (ii) *task completion capacity*, the number of tasks which can be in their completion process at the incident site per time period; and (iii) prior completion of the *safety task* before completing certain other tasks, which represents the operations dedicated to preserving human safety and declaring the incident site suitable for conducting a response effort. These factors can cause the idle time illustrated in Figure 3.1.

Task pairs model the consequences due to oil spread, and the resulting additional effort required to restore shoreline areas, if certain tasks are completed late. These pairs include certain *initial tasks* that have a deadline which, if not met, require the completion of *follow-on tasks*, instead. The resources required for a follow-on task are the sum of those required for the paired initial task, combined with the resources required for shoreline cleanup operations. *Deadlines* are generated for all initial tasks as determined by the amount of time estimated until shoreline impact in order to generate the resource requirements for their follow-on tasks (Aagaard, Pease, Roach, & Salo, 1989; MBC Applied Environmental Sciences, 2003; Danielson et al., 2006; Alaska Clean Seas, 2012, 2013; Hongxia, Huiwu, Qi, Daolong, & Na, 2013). For example, an incident might require a recovery task to be completed before day 6, when the spillage would otherwise come ashore and require a follow-on shoreline cleanup task in addition to what has already been completed. In this example, the follow-on task would require the same resources as its paired initial task (e.g., the recovery task) plus the additional resources required if the deadline were missed (e.g., the shoreline cleanup task) in order to incorporate the effort made for tasks completed pre- and post-deadline. Since the resources required for the initial task are also required for the follow-on task, the task pair structure can be considered as modeling the arrival of resources to the spill incident which remain on location until they can cumulatively be used to complete the initial task. Note, however, that the model can determine whether a deadline will be missed for an initial task, and it may elect not to deploy the necessary resources even if this task's deadline is attainable (in favor of deploying resources for other initial tasks that will meet their deadlines), so that the resources arrive at the same time as the resource that causes a bottleneck in the completion of the initial task. This is believed to be the first model to examine consequences of missed deadlines in terms of needing to complete a different task to mitigate the impact of the missed deadline.

Decisions from the resource allocation component impact the amount of resources available to the response network via *stockpile configuration decisions* and *infrastructure investment decisions*. Stockpile configuration decisions can be manipulated through resource allocation decisions, including transporting a resource between response sites, purchasing, or retaining until the next time period. Infrastructure investment decisions make improvements to two distinct *infrastructure design option* classes by deciding the options that are currently available and whether to invest. These design options include: *capability options*, which allow for pre-staging certain resources; and *capacity options*, which improve storage capacity for certain resources. Expert opinion noted that, while a resource is stored in only one capacity class, it can require multiple capability classes. For example, a landing strip, refueling depot, and aircraft hangar may be constructed in a response site. The addition of the landing strip and refueling depot would provide the response site with the *capability* to store aircraft, and the hangar would provide the site with the *capacity* to store multiple aircraft.

The remainder of this Chapter is organized as follows. Section 3.1 discusses the objective of minimizing total weighted response time for the set of potential oil spill incidents. Section 3.2

introduces the oil spill response constraints and discusses the decisions necessary to generate the task schedule for a response to an incident. Section 3.3 introduces the resource allocation constraints that influence the stockpile configuration which impact the responses to incidents. Section 3.4 discusses the theoretical complexity of the model. Section 3.5 describes the process of gathering and incorporating critical feedback into the model.

Table 1: Set Definitions

Set Name	Definition
E_t	the spill incidents, occurring at each time period $t \in T$.
L	the tasks.
P	the task pairs.
T	the resource allocation time periods.
S	the incident response time periods.
I	the resources.
O^{CB}	the capability design options.
O^{CP}	the capacity design options.
$I(o)$	the set of resources requiring either design option $o \in O^{CB}$ or $o \in O^{CP}$ in order to be stored in a response site.
J	the response sites.

Table 2: Variable Definitions

Variable Name	Definition
π_{l_1et}	whether initial task $l_1 \in L$ or follow-on task $l_2 \in L$, each of task pair $(l_1, l_2) \in P$, is completed for spill incident e at time period t. If initial task $l_1 \in L$ is completed (i.e. its deadline is met), then $\pi_{l_1et} = 1$, $\pi_{l_1et} = 0$ otherwise.
τ_{let}	the completion time of task l for spill incident e at time period t. Completion times are measured in units of incident response time periods ($s \in S$).
δ_{ijlest}	whether resource i is mobilized from response site j for task l for spill incident e in incident response period s at time period t.
Δ_{lest}	whether task l is completed for spill incident e during incident response time period s at resource allocation time period t. If task l is completed, then $\Delta_{lest} = 1$, $\Delta_{lest} = 0$ otherwise.
ζ_{ijlet}	whether resource i has been transported from response site j to be deployed for task l for spill incident e at time period t. If resource i is transported and deployed, then $\zeta_{ijlet} = 1$, $\zeta_{ijlet} = 0$ otherwise.
χ_{ijelt}	the amount of resource i mobilized from response site j to spill incident e for task l at time period t.

Continued on next page

Table 3.2 – continued from previous page

Variable Name	Definition
ν_{est}	whether the safety task f has been completed by capacity period s in response to spill e at time period t. If task f has been completed, then $\nu_{est} = 1$, $\nu_{est} = 0$ otherwise.
Ω_{ijt}	the amount of resource i on hand in response site j at time period t.
α_{jot}	whether infrastructure capability option $o \in O^{CB}$ is available in response site j at time period t. If design option $o \in O^{CB}$ is available, then $\alpha_{jot} = 1$, $\alpha_{jot} = 0$ otherwise.
β_{jot}	whether infrastructure capability option $o \in O^{CB}$ is built in response site j at time period t. If design option $o \in O^{CB}$ is built, then $\beta_{jot} = 1$, $\beta_{jot} = 0$ otherwise.
λ_{jot}	the amount of infrastructure capacity option $o \in O^{CP}$ currently available in response site j for $o \in O^{CP}$ at time period t.
Λ_{jot}	the amount of infrastructure capacity option $o \in O^{CP}$ to build in response site j for $o \in O^{CP}$ at time period t.
ϕ_{ijt}	the amount of resource i purchased in response site j between periods $t-1$ and t.
σ_{ijkt}	the amount of resource i shipped from response site j to response site k between periods $t-1$ and t.
ψ_{ijt}	the amount of resource i to be held in response site j from time period $t-1$ to t.

Table 3: Parameter Definitions

Parameter Name	Definition
A_t	the spending budget for resource purchasing, shipping, and lifecycle costs at time period t.
a^1_{ijt}	the purchasing cost of resource i in response site j at time period t.
a^2_{ijkt}	the shipping cost of resource i from response site j to response site $k \in J$ at time period t.
a^3_{ij}	the maintenance cost of resource i in response site j.
B_t	the spending budget for infrastructure expansion at time period t.
b_{jot}	the infrastructure expansion cost in response site j for design option o at time period t.
c_{jot}	the capacity for resource i in response site j of design option o.
d_{le}	the deadline required to complete task l for spill incident e.
f	the safety task within L.
g_{il}	the number of units of deployment capacity required to deploy resource i for task l.
(l_1, l_2)	a pair of tasks wherein if the deadline for initial task l_1 is missed, then the completion of follow-on task l_2 is required, instead. If the deadline is met for l_1, then the completion of l_2 is unnecessary.

Continued on next page

Table 3.3 – continued from previous page

Parameter Name	Definition
m_{je}	the transport time required for resources from response site j arriving at spill incident e.
n_{ilet}	the time required to deploy resource i for task l for spill incident e at time t.
r_{ile}	the amount of resource i required for task l in response to spill incident e.
u_j	the upper bound on the number of mobilized resources from response site j during incident response time period s.
u_e	the upper bound on the number of tasks that can be processed for completion at spill incident e during incident response time period s.
w_{let}	the weight for completing task l in response to spill e at time period t.
z_{io}	the size of resource i for design option o.

3.1 OBJECTIVE FUNCTION

The objective function is to minimize the total weighted completion times of each task $l \in L$ required in the response to each incident $e \in E_t$ occurring in time period t. This completion time is represented by τ_{let}, and w_{let} can weight the completion time for incident e and/or task l in order to increase the priority of responding to an incident, completing a task, or both. For example, increased weight can be applied to incidents having higher likelihoods of occurrence, or to certain tasks that are more critical. The resulting problem is similar to that of minimizing total weighted completion times (see, for instance, (Pinedo, 2008)), with a few novel features which are discussed throughout this section. The objective function is expressed as

$$min \sum_{l \in L} \sum_{e \in E_t} \sum_{t \in T} w_{let} \tau_{let}.$$

The decision variables denoting the completion time of a task l for an incident e at time period t (τ_{let}) depend directly on the oil spill response component (Section 3.2) and indirectly on the resource allocation component (Section 3.3).

3.2 OIL SPILL RESPONSE COMPONENT

Each incident e requires the completion of certain tasks from the set l along the response time horizon S in order to generate a value for τ_{let}. These completions depend on the total time required to transport and prepare for use each necessary resource i arriving from one (or more) sites j, given the conditions present at time period t of the resource allocation time horizon. These decisions are impacted by the stockpile configuration decisions, the amount of resource $i \in I$ at response site $j \in J$

at time period $t \in T$ of the resource allocation horizon (Ω_{ijt}). For a specific incident, these variables then limit the decisions made by the oil spill response component in responding to a specific incident.

Task pairs $(l_1, l_2) \in P$ are used to model the impact of missing deadlines by way of linked initial ($l_1 \in L$) and follow-on ($l_2 \in L$) tasks, and the selected task defines the resources to mobilize from the response network J. Let d_{l_1e} represent the deadline for initial task l_1 required for spill incident e, and r_{ilet} represent the amount of resource i required for task l of spill incident e. An initial task l_1 that is selected for completion ($\pi_{l_1et} = 1$) must be done so by its deadline (Constraints 3.1). Failing to complete l_1 by its deadline ($1 - \pi_{l_1et} = 1$) results in follow-on task l_2 to be completed, instead (Constraints 3.2). The selected task (initial or follow-on) must have its required amount of resource i (r_{ilet}) met by mobilizing resource i from the stockpile of one or more sites j in the response network (decisions χ_{ijlet}) which are expressed in Constraints 3.3, 3.4. The task deadlines and resource requirements constraints are expressed as

$$\tau_{l_1et} - d_{l_1e}\pi_{l_1et} \leq 0 \text{ for } l_1 \in L, e \in E_t, t \in T, \tag{3.1}$$

$$\tau_{l_2et} - (d_{l_1e} + 1)(1 - \pi_{l_1et}) \geq 0 \text{ for } (l_1, l_2) \in P, e \in E_t, t \in T, \tag{3.2}$$

$$\sum_{j \in J} \chi_{ijl_1et} - r_{il_1et}\pi_{l_1et} \geq 0 \text{ for } i \in I, l_1 \in L, e \in E_t, t \in T, \tag{3.3}$$

$$\sum_{j \in J} \chi_{ijl_2et} - r_{il_2et}(1 - \pi_{l_1et}) \geq 0 \text{ for } i \in I, (l_1, l_2) \in P, e \in E_t, t \in T. \tag{3.4}$$

In order for any amount of resource i to be mobilized from site j for use in task l for incident $e \in E_t$ (variable χ_{ijlet}), it is necessary for that resource to be transported to the incident location and then deployed. The binary decision variable ζ_{ijlet} will be equal to 1 should resource i be transported from site j for task l at incident $e \in E_t$ and Constraints 3.5 enforce the relationship between ζ_{ijlet} and χ_{ijlet}. The amount of resource i mobilized from site j is limited by how much is currently stockpiled (Ω_{ijt}) which is modeled by Constraints 3.6, and this amount is driven by the resource allocation decisions discussed in Section 3.3. It is then necessary to decide the time period s which resource i will be mobilized from j ($\delta_{ijlest} = 1$ if we mobilize i from j in s). Constraints 3.7 enforce that should any amount of resource i be transported from j and deployed for task l for $e \in E_t$, it must be mobilized in some time period $s \in S$. These resource mobilization and deployment constraints are expressed as

$$\chi_{ijlet} - r_{ilet}\zeta_{ijlet} \leq 0 \text{ for } i \in I, j \in J, l \in L, e \in E_t, t \in T, \tag{3.5}$$

$$\sum_{l \in L} \chi_{ijlet} - \Omega_{ijt} \leq 0 \text{ for } i \in I, j \in J, e \in E_t, t \in T, \tag{3.6}$$

$$\zeta_{ijlet} - \sum_{s \in S} \delta_{ijlest} \leq 0 \text{ for } i \in I, j \in J, l \in L, e \in E_t, t \in T. \tag{3.7}$$

In order for task l to be completed in time period s for incident $e \in E_t$ ($\Delta_{lest} = 1$), all of its required resources must be mobilized from their selected sites in the response network ($\delta_{ijlest} = 1$ for some site j and period s), transported to the location of the incident (m_{ije}), and then deployed at the incident (n_{ilet}). Constraints 3.8 enforce this relationship based on whether site j was selected for transporting resource i for task l (ζ_{ijlet}). Constraints 3.9 then calculate the completion time of a task (τ_{let}) based on the selected time period of completion of task l, while Constraints 3.10 ensure that each task is only completed once. The completion time constraints are represented as

$$\begin{aligned} (m_{ije} + n_{ilet})\zeta_{ijlet} + \sum_{s \in S}(s-1)\delta_{ijlest} - \sum_{s \in S} s\Delta_{lest} \leq 0 \\ \text{for } i \in I, j \in J, l \in L, e \in E_t, t \in T, \end{aligned} \tag{3.8}$$

$$\tau_{let} - \sum_{s \in S} s\Delta_{lest} \geq 0 \text{ for } l \in L, e \in E_t, t \in T, \tag{3.9}$$

$$\sum_{s \in S} \Delta_{lest} \leq 1 \text{ for } l \in L, e \in E_t, t \in T. \tag{3.10}$$

Additional considerations can delay the completion time of task l (Figure 3.1): the resource mobilization capacity of site j, the task completion capacity at incident e, and the safety task's completion time. The capacity of site j to mobilize resources simultaneously for all tasks (u_j) is limited per response time period s (Constraints 3.11). At incident e, the capacity to simultaneously process tasks for completion is limited (u_e). Constraints 3.12 ensure that the number of units required for deploying resources at time s does not exceed u_e. Note that task l is currently being processed for completion if its resources are deployed from time s through time $s + n_{ilet} - 1$, and we assume that all resources required for task l are deployed simultaneously. Experts noted that u_j, u_e do not change seasonally, given the ability for work crews to manage the tasks required for different incidents occurring in different seasons (e.g., $e \in E_t$).

The safety task $f \in L$ must be completed prior to (safely) completing certain other tasks (where $\nu_{est} = 1$ if this task is completed at or before s). If task $l \in L \setminus \{f\}$ is completed, then the safety task f must have been previously completed with sufficient time to deploy its resources (Constraints 3.13). In order for the safety task f to have been completed at or before time s, it must either have been completed at time s, or completed in the previous time period (Constraints 3.14). Additionally, the safety task must have been competed in the first time period ($s = 1$) for it to be completed at or before at that time (Constraints 3.15). Resource mobilization capacity, task completion capacity, and completion of the safety task prior to completing other tasks constraints are represented as follows

$$\sum_{i \in I} \sum_{l \in L} \delta_{ijlest} - u_j \leq 0 \text{ for } j \in J, e \in E_t, s \in S, t \in T, \tag{3.11}$$

$$\sum_{l \in L} \sum_{s'=s}^{min(s+n_{ilet}-1,|S|)} g_{il} \Delta_{les't} - u_e \leq 0 \text{ for } i \in I, e \in E_t, s \in S, t \in T, \tag{3.12}$$

$$\Delta_{lest} - \nu_{e(d-n_{ilet})t} \leq 0 \text{ for } l \in L \setminus \{f\}, e \in E_t, s \in S, t \in T, \tag{3.13}$$

$$\nu_{est} - \Delta_{fest} - \nu_{e(d-1)t} = 0 \text{ for } f \in L, e \in E_t, s \in S, t \in T, \tag{3.14}$$

$$\nu_{e1t} - \Delta_{le1t} \leq 0 \text{ for } e \in E_t, 1 \in S, t \in T. \tag{3.15}$$

3.3 RESOURCE ALLOCATION COMPONENT

The resource allocation component decisions are made along a time horizon T, for a set of resources I sited within a set of infrastructures O across a set of response sites J. These decisions impact the task completion time, τ_{let}, by altering the types and amounts of resources i stockpiled in site j, Ω_{ijt}. In each time period t, the resource allocation decisions are made by purchasing, transporting, and maintaining resources subject to budget level A_t. These decisions alter the flow balance of resources between time periods, and the stockpile configuration Ω_{ijt} is decided as a result. Resource i can be stockpiled in response site j at time period t if it was previously transported to response site $k \in J$ (σ_{ijkt}), purchased (ϕ_{ijt}), or held over (ψ_{ijt}). Then, the stockpile at time t is equal to the in-flow of resource i from the previous time period, which is the amount purchased and held-over in site j, and transported into site j from site $k \in J : k \neq j$ (Constraints 3.16). The stockpile at time t is also equal to the out-flow of resource i at the current time period, which is the amount to be held over in site j and transported out of site j to site $k \in J : k \neq j$ (Constraints 3.17). The total cost from the resource allocation decisions, from purchasing (a^1_{ijt}), transporting (a^2_{ijt}), and holding (a^3_{ijt}), must be no greater than the resource allocation budget (Constraints 3.18). The resource allocation decisions are represented as

$$\phi_{ij(t-1)} + \sum_{k \in J : k \neq j} \sigma_{ikj(t-1)} + \psi_{ij(t-1)} = \Omega_{ijt} \text{ for } i \in I, j \in J, t \in T, \tag{3.16}$$

$$\psi_{ijt} + \sum_{k\in J:k\neq j} \sigma_{ijkt} = \Omega_{ijt} \text{ for } i \in I, j \in J, t \in T, \tag{3.17}$$

$$\sum_{i\in I}\sum_{j\in J}\{a^1_{ijt}\phi_{ijt} + \sum_{k\in J:k\neq j} a^2_{ijkt}\sigma_{ikjt} + a^3_{ij}\psi_{ijt}\} \leq A_t \text{ for } t \in T. \tag{3.18}$$

In response site j, each resource must be stockpiled within one class of capacity infrastructure options but may require multiple classes of capability infrastructure options. The investments made to build these infrastructures represent the dynamic network expansion decisions. Resource allocation decisions, and therefore Ω_{ijt}, are impacted by the infrastructure at j within the two distinct infrastructure design option classes: capability options (O^{CB}); and capacity options (O^{CP}). A resource is stored in one O^{CP} class, but can require multiple O^{CB} classes. Therefore, $I(o)$ is defined to be the set of resources that require option o in order to be stored at site j, such that $I(o_1) \cap I(o_2) = \emptyset \ \forall (o_1, o_2) \in O^{CP}$.

Four variables comprise the set of infrastructure investment decisions. The number of capacity options O^{CP} in site j at time t are determined by the number built (Λ_{jot}) in addition to the number available (λ_{jot}). The capability options O^{CB} in site j are determined similarly, where o is built ($\beta_{jot} = 1$) or is available ($\alpha_{jot} = 1$). For each infrastructure option o, the size of resource i is defined (z_{io}), and must not exceed the storage capacity within that option (c_{jot}), where c_{jot} for $o \in O^{CB}$ acts as a 'Big-M' (Constraints 3.19, 3.21). The types of infrastructure in site j at time t depend on which options o are available or built in the previous time period (Constraints 3.20, 3.22). The infrastructure investment decisions are represented as

$$\sum_{i\in I(o)} z_{io}\Omega_{ijt} - c_{jot}\lambda_{jot} \leq 0 \text{ for } j \in J, o \in O^{CP}, t \in T, \tag{3.19}$$

$$\lambda_{jo(t-1)} + \Lambda_{jo(t-1)} - \lambda_{jot} = 0 \text{ for } j \in J, o \in O^{CP}, t \in T, \tag{3.20}$$

$$\sum_{i\in I(o)} z_{io}\Omega_{ijt} - c_{jot}\alpha_{jot} \leq 0 \text{ for } j \in J, o \in O^{CB}, t \in T, \tag{3.21}$$

$$\alpha_{jo(t-1)} + \beta_{jo(t-1)} - \alpha_{jot} = 0 \text{ for } j \in J, o \in O^{CB}, t \in T, \tag{3.22}$$

$$\sum_{j\in J}\sum_{o\in O} b_{jot}(\beta_{jot} + \Lambda_{jot}) \leq B_t \text{ for } t \in T. \tag{3.23}$$

3.4 THEORETICAL COMPLEXITY

The theoretical complexity of the model is considered in terms of both modeled components. Regarding the resource allocation component, consider the decisions to mobilize and deploy a single resource from every response site. If the deployment time is considered to be a transportation cost, then minimizing this objective is a special case of the facility location problem - since we may need to build an infrastructure capability at the site - which is NP-hard. Regarding the oil spill response component, an argument similar to the complexity proof of total weighted tardiness (Pinedo, 2008) can be transformed into an argument for the problem of total weighted response time with follow-on tasks. Therefore, given that these problems are also NP-hard, the problem (e.g., consisting of both components) is also NP-hard. The IP model performs sufficiently to examine the problem of improving weighted oil spill response times in the Alaskan Arctic as a function of dynamic resource allocation and infrastructure investment decisions. However, additional work may be necessary to address the complexity of this problem when applied to other regions.

3.5 MODEL DEVELOPMENT AND THE SYSTEMS DEVELOPMENT LIFE CYCLE

The steps in the Systems Development Life Cycle (SDLC) (Centers for Medicare and Medicaid Services, 2005; Blanchard & Fabrycky, 2006; Post & Anderson, 2006; Pendharkara, Rodgerb, & Subramanian, 2008; Radack, 2009; Marakas & O'Brien, 2010; He et al., 2015) provided the backdrop for the model development activities described in this chapter. The SDLC process divides a project into phases in order to plan, create, test, and deploy a software or hardware system, which can be comprised of software and/or hardware (Centers for Medicare and Medicaid Services, 2005; Blanchard & Fabrycky, 2006; Post & Anderson, 2006). During this process, incorporation of feedback and review of software and models by domain experts helped establish the requirements and design of the final product, which is important to robust software and model development efforts (Post & Anderson, 2006; Pendharkara et al., 2008; Radack, 2009; Marakas & O'Brien, 2010). A complete description of activities in each of the SDLC phases that were undertaken is provided in Appendix C. The SDLC process can vary by use-case, but the following phases and associated descriptions are common for software and hardware systems alike (Blanchard & Fabrycky, 2006; Post & Anderson, 2006; Pendharkara et al., 2008; Radack, 2009; Marakas & O'Brien, 2010; He et al., 2015):

1. Requirements Determination: determination of the project requirements and specifications. The need for the project is determined, the final product's functionality is specified, and the technical requirements of the final product are agreed upon by those involved. The requirements produced during this phase are general in nature, resulting in an initial concept for the product without a plan for its development. For example, the Requirements Document presented in Appendix D demonstrates the general nature of the requirements, and specifies the features

that are planned and agreed upon by the domain experts associated with the development of this work.

2. Design: creation of a specific plan to meet the specifications of the Requirements Determination phase. The design of the final product follows on from the general requirements developed previously, and the specific details pertaining to the realization of each requirement are actualized. While the product's requirements outline which features must be included, the product's design specifies how each feature will be realized. For example, the design of this work involved the development of the mixed-integer linear program (e.g., the model) discussed previously in this chapter.

3. Development: generation of code and other software, and/or generation of a functional hardware prototype. For software, the source code is written and compiled into a functional form; for hardware, a working prototype is developed. For example, the software development for this work involved coding the model within a programming language, along with the implementation of a dataset for use with the case study discussed in later sections.

4. Testing: assessment of the software or hardware to determine functionality and fulfillment of design requirements. For example, a software package would be examined for verification and validation of its core functions, and the source code would be de-bugged so that errors are fixed.

5. Distribution: delivery of the final product to the client. For example, a software package would be physically or electronically distributed to the intended user(s).

6. Use and Maintenance: operation of the final product by the client, and sustenance of the product for the client. For example, the intended user(s) would begin to use the software to fulfill its specified purpose, and a party would focus on maintaining the software installation or database in order to ensure usability.

7. Disposal: execution of end-of-life activities for the product. For example, if the life cycle of a software product has concluded, then the product might be removed from the user's computing hardware, and all interconnections to the software from other systems would be terminated.

4. COMPUTATIONAL ANALYSIS

In this chapter, the development and analysis of test instances from a realistic case study of the Arctic is presented. Section 4.1 discusses the method to generate the test instances from the case study. Computational difficulty of these tests is discussed (Section 4.2), and their results are presented (Section 4.3).

4.1 CASE STUDY: ARCTIC OIL SPILL RESPONSE

A case study was developed to address the case study questions (Section 1) and to test the model. The information that was utilized, from public sources and expert interviews, was vetted by oil spill response experts in order to develop test instances that encompass realistic features pertaining to oil spill response in the Arctic. This data set focused on the Alaskan Arctic which includes the Beaufort and Chukchi seas as well as the North Slope, i.e., the coastal region of Northern Alaska. Figure 4.1 illustrates the response sites and potential spill incidents considered in the case study; these sites and incidents are discussed in the following sections. Section 4.1.1 discusses Arctic oil spill response sites that comprise the response network. Section 4.1.2 discusses temporal characteristics and their impact on operations in the region. Section 4.1.3 discusses the method developed to generate potential spill incidents. Section 4.1.4 discusses how the tasks and resources are determined for a specific spill incident. Appendix B provides more details surrounding the discussions in this section.

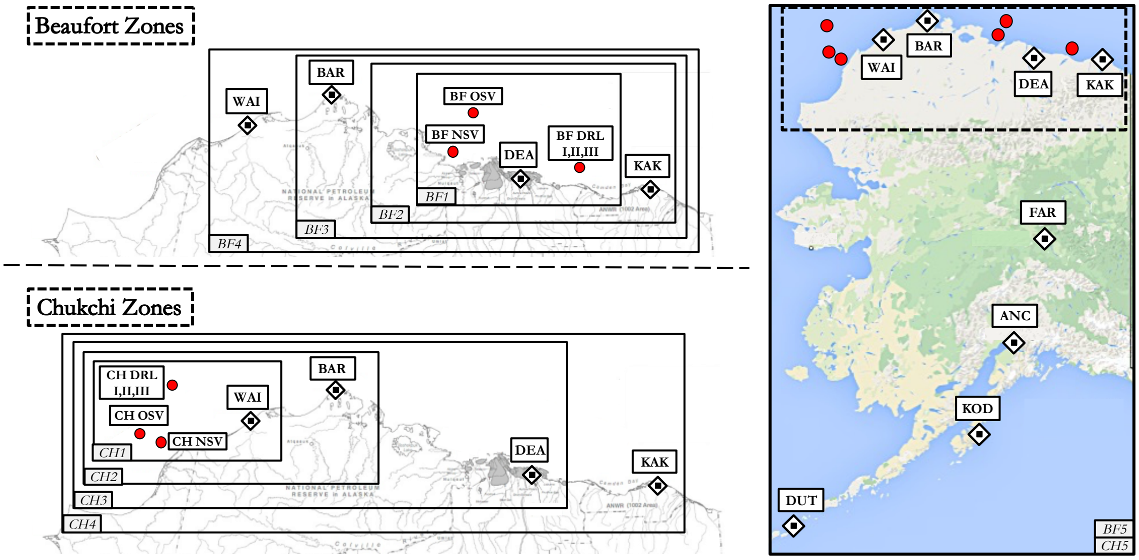

Figure 4.1: The two categories of response zones, labeled by increasing distance from the incident locations. Each response zone category is comprised of four zones on the North Slope (BF1-BF4, CH1-CH4) and one zone encompassing the entire state (BF5,CH5). Beaufort Sea incidents (upper left): Beaufort Drill Incident I - Beaufort Drill Incident III (e.g., BF DRL I,II,III), Beaufort Nearshore Vessel Incident (e.g., BF NSV) and Beaufort Offshore Vessel Incident (e.g., BF OSV). Chukchi Sea incidents (lower left): Chukchi Drill Incident I - Chukchi Drill Incident III (e.g., CH DRL I,II,III), Chukchi Nearshore Vessel Incident (e.g., CH NSV) and Chukchi Offshore Vessel Incident (e.g., CH OSV).

4.1.1 RESPONSE SITES

Eight communities were deemed by domain experts to be suitable to act as response sites based on their available infrastructure, population, and location. These include four North Slope and Northwest Borough villages spread across the Beaufort and Chukchi energy exploration regions, each with at most 5,000 residents (e.g., Barrow, Deadhorse, Kaktovik, and Wainwright), in addition to four communities in central and southern Alaska (e.g., Anchorage, Dutch Harbor, Fairbanks, and Kodiak). Two sites on the North Slope were identified as *primary response sites*, capable of mobilizing resources directly to the incident locations, with one in the Beaufort region (e.g., Deadhorse) and one in the Chukchi region (e.g., Wainwright), as identified in current federally- and state-required oil spill response contingency plans (U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region, 2011a, 2011b). The remaining six sites were identified as *secondary response* *sites*, where resources are first transported to a primary response site prior to mobilization. We can group the response sites into two types of *response zones*, *Beaufort response zones* and *Chukchi response zones*, as defined by the geographic proximity of each site to the incidents in the Beaufort Sea and Chukchi Sea, respectively. Analysis of response zones permits examination of response site criticality by examining how the timeliness of equipment arrival impacts decisions surrounding infrastructure investment, resource allocation, and resource deployment. Summary characteristics for the eight sites including the hub of Anchorage, a secondary response site in the south of Alaska through which resources arrive from other Oil Spill Response Organizations (OSRO's) within and outside the state, can be found in Appendix B. The offshore resources necessary for drill incidents are assumed to be deployed by oil companies and OSRO's, and these resources have negligible transit times to the drilling wells given that they are pre-staged locally (U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region, 2011a, 2011b). Additionally, these pre-staged resources are assumed to supply 50% of the offshore vessel incidents' requirements, given expert feedback that these resources cannot currently be sited in the Arctic.

4.1.2 TEMPORAL CHARACTERISTICS

Response tactics for all oil spill incidents are considered during the short, 4-month period (June - September) when temperature and ice conditions permit oil exploration, exploratory drilling, and support vessel navigation. Tactics are not considered during the 1-month periods (May, October) when significant ice is present in waterways due to changing seasons. Tactics for sustained drilling operations are also considered during the 6-month period (November - April) comprising winter seasons, given the ability for these operations to occur in the presence of solid ice. Spill response during these seasons requires different tactics compared with during summer seasons due to the presence of solid pack ice, and although the total weighted response time for an incident is impacted by the set of tasks required each season, seasonality does not necessarily impact spill location. Winter response tactics also require fewer types of resources, and in fewer numbers, than summer seasons (Alaska Clean Seas, 2012), and expert interviews suggested that infrastructure investments are impossible during winter time periods. Given these considerations, and that the functional form of the solutions for summer and winter seasons were found to be similar, the driver of the model's decisions is the improvement of summer time periods. Therefore, despite the model's ability to capture seasonality, only the results from summer time periods are presented in Section 4.3, given that each winter season is utilized in order to prepare for the following summer season. Thus, while twenty resource allocation time periods were generated that represent these summer and winter seasons over the course of ten years, only trends regarding the ten summer seasons are considered in Section 4.3. For each potential incident occurring in each of these seasons, 28 response time horizon periods were generated, representing six-hour periods over the course of one week.

4.1.3 GENERATING POTENTIAL SPILL INCIDENTS

The attributes of each spill incident determine the response tactics necessary based on the following descriptors: (i) incident source, such as vessel spillage or drill platform blowout; (ii) volume and type of product discharged; (iii) distance from shore; (iv) personnel safety considerations; and (v) environmental and geographical factors (Alaska Clean Seas, 2012). Three types of incident sources were selected, consistent with required federal and state oil spill response contingency plans, to occur in each sea: a drilling well blowout, a nearshore-, and an offshore-vessel incident (U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region, 2011b, 2011a; Papp, 2013; National Academy of Sciences, 2014). The nearshore- and offshore vessel incidents were generated for the Beaufort and Chukchi Seas based on OSRO guidelines (United States Coast Guard, 2013), in order to examine the resource configurations necessary to support these independent of the drill incidents. Three different discharge volume levels, ordered from least to greatest, were modeled for incidents in the Beaufort Sea (e.g., Beaufort Drill Incident I - Beaufort Drill Incident III) and Chukchi Sea (e.g., Chukchi Drill Incident I - Chukchi Drill Incident III), as estimated from U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region (2011a, 2011b). One discharge volume level was modeled for nearshore- and offshore-vessel incidents in the Beaufort Sea (e.g., Beaufort Nearshore Vessel Incident and Beaufort Offshore Vessel Incident, respectively) and Chukchi Sea (e.g., Chukchi Nearshore Vessel Incident and Chukchi Offshore Vessel Incident, respectively), as estimated from United States Coast Guard (2013).

4.1.4 DETERMINING TASKS AND RESOURCES FOR A SPECIFIC SPILL INCIDENT

Six *task strategies* were considered, which grouped the modeled tasks by function: three strategies pertained to recovering the spill volume (e.g., mechanical recovery, in-situ burning, and dispersant application); and three pertained to non-recovery operations (e.g., human safety, logistics, and spill trajectory tracking) (Alaska Clean Seas, 2012). Domain experts identified the task weights based on these functions, and tasks were considered independent of each other; weights for disposal and logistics were half the weights for all other tasks. Additionally, experts noted that incidents can occur that only require spill tracking, and none of the other five strategies would be utilized. The analysis presented in Section 4.3 excludes these types of incidents, and instead is focused on response efforts which also require a combination of the other task strategies.

The initial and follow-on task lists and associated resource requirements were generated for each of the eight task pairs as necessary to address the strategies for each incident. For recovery strategies, tasks representing both containment and recovery (e.g., mechanical recovery strategy), in-situ burning, and dispersant application were considered. Please see Appendix B for details on how the resource types and requirements were calculated for these tasks. For all other strategies, disposal, logistics, safety, and tracking tasks were considered. The safety task (e.g., f) takes priority over all tasks, except logistics and tracking, given the nature of these tasks and their ability to be completed without providing further risk to human safety.

Fourteen resource types were modeled, which represent generic forms of the most significant equipment required for the modeled tasks: Small Aircraft; Large Aircraft; Offshore Boom; Near Shore Boom; In-Situ Burning Equipment; Dispersant; Mobile Command Facility; Near Shore Vessel; Offshore Vessel; Tank Vessel; Storage Bladder; Offshore Skimming Vessel; Skimmer System; and Ground Vehicles. These resources were dependent on the availability of specific infrastructure design options; for instance, a near shore vessel requires gravel pad space for storage on land, a refueling source, and a small boat launch for deployment at an incident site.

The Bureau of Safety and Environmental Enforcement (BSEE) has examined the tasks and resource requirements for oil spill response in the Arctic, in order to develop standards and guidelines for the creation of Oil Spill Response Plans (OSRP's) in support of offshore (e.g., >200 nautical miles) energy exploration efforts (see, for instance, Robertson (2014); Conroy, Ananth, and Tuttle (2016)). As a result, certain publicly-available tools have been developed by BSEE to support the creation of OSRP's, including:

- The Western Response Resource List (WRRL): A repository of known oil spill response equipment stockpiles in the Pacific Northwest. Information contained within the WRRL is highly detailed, downloadable from the internet in several formats, and can be utilized during oil spill response efforts (Genwest Systems, Inc., 2016b).
- Response System Planning Calculators: Tools utilized to estimate the potential performance of oil spill response equipment, as applied to mechanical recovery, in-situ burning, and dispersants response tasks. Given input information regarding equipment type and specifications, the user is provided with an estimate of the equipment's performance over time (Genwest Systems, Inc., 2016a).

4.2 COMPUTATIONAL ANALYSIS: TEST INSTANCES AND SOLUTION TIMES

The problem is analyzed for computational difficulty in terms of the test instances derived from the case study (Section 4.1), and in terms of additional instances developed to reveal further insight and trends in problem difficulty. All instances were tested under CPLEX 12.6 on an 8-core computer with 64 GB of RAM, and these were run until the optimality gaps were less than 4.00%. The goal is to examine and compare solutions of sufficient quality given variation in the parameter(s) of interest as indicated by the (relatively) small optimality gaps. Table 4.1 provides summary characteristics and computational runtimes for the test instances.

Certain instances are defined by varying the budget for resource allocation decisions (A_t). These budget instances are defined by the percentage difference between the budget level required to maintain the initial stockpile, and the minimum budget level required to achieve the best possible stockpile. For instance, the 0.00% level permits no resource allocation decisions due to stockpile maintenance costs, whereas 25.00% permits some of these decisions. The budget for infrastructure investment decisions (B_t) is fixed for these instances. Instances feature a resource allocation time horizon length of $T = 20$ unless otherwise indicated. The test instances are represented as follows:

(i) Base network resource allocation budget instances: $A_1, A_2, \ldots, A_7$, defined by varying the resource allocation budget A_t for the base response network described in Section 4.1.1. These budget instances are examined so that the functional form of the solutions and patterns pertaining to resource stockpile configuration can be considered.

(ii) Enhanced network resource allocation budget instances: $D_1, D_2, \ldots, D_7$, defined by varying the resource allocation budget A_t for the base response network enhanced by the inclusion of *four* capability-limited DEW Line sites in the Chukchi Sea region. These budget instances examine trends in problem difficulty as the size of the response network grows and provide insights into the impact on response capabilities with a larger network. Additional discussion of these sites can be found in Appendix B.

(iii) Semi-enhanced network instances: $D_2^*, D_3^*, \ldots, D_7^*$, defined by varying the resource allocation budget A_t for the response network enhanced by the inclusion of *two* capability-limited DEW Line sites in the Chukchi Sea. These instances were developed outside of the case study in order to examine trends in problem difficulty as the size of the response network grows.

(iv) Infrastructure investment budget instances: B_{min} and B_{max}, defined by reduced and increased values of budget B_t, respectively. These budget instances are examined so that the impacts from restricting infrastructure investment decisions can be explored. Two levels of the infrastructure budget are considered: the 8% level permitted stockpiling only land-based resources; and an unconstrained budget. The remaining instances were also tested with an unconstrained infrastructure investment budget.

(v) Delayed task completion instances: F_{min} and F_{max}, defined by reduced and increased completion times of the safety task f, respectively. These task completion instances are examined so that the impacts from delayed safety task completion time can be explored.

(vi) Resource deployment instances: u_{min} and u_{max}, defined by reduced and increased values of the site-based resource mobilization limiter u_j. These resource deployment instances are examined so that the impacts from limiting resource mobilization from the response sites can be explored. u_{max} includes the most unconstrained problem conditions for this study.

(vii) Extended time horizon instances: $A^*_{01}, \ldots, A^*_{04}$, defined by varying the resource allocation budget A_t for the base response network under an extended time horizon ($T = 30$). These instances were developed outside of the case study in order to examine trends in problem difficulty as the number of time periods grows. Note that the budgets are significantly reduced in order to ensure that resource allocation decisions will be made over the time from periods 20 to 30.

As seen in Table 4.1, instances of highly-constrained budget levels, combined with an extended time horizon length (e.g., $A^*_{01}, \ldots, A^*_{04}$), demonstrate significant increases in problem difficulty. Increasing the network's size also increases problem difficulty, and it is noted that this difficulty increases as more sites are introduced to the network, as observed by comparing runtimes for the base network instances with the semi-enhanced and enhanced network instances (e.g., instances D_x versus D^*_x). However, domain experts observed that, in the context of the case study setting (Section 4.1), the practical need to solve the problem with an increased network size, and for 30 or more time periods, is reduced. Although run times may approach 24 hours, these are strategic, long-term decisions that do not require real-time decision support. Therefore, problems of $T = 30$ time periods could be examined, but the size of the problem that is solvable without customized solution approaches is more obvious in this analysis. Therefore, these runtimes are sufficient for the purposes of this analysis, and the need exists for future work to explore methods to promote solvability for case studies representing larger data sets.

Problem difficulty is reduced for the most- and least-constraining values of the resource allocation budget (e.g., A_1, D_1 and A_7, D_7) and infrastructure investment budget (e.g., B_{min} and B_{max}). These times also demonstrate a gradual rise and fall in difficulty around certain spikes (e.g., A_4, D^*_5, and D_3). Increasing the time horizon length (e.g., instances A_x versus A^*_x) does not necessarily follow this trend, but in general, this aspect of the problem does not significantly increase the problem's difficulty, given the tendency to reach a steady-state solution as discussed in Section 4.3.1. Relieving sources of bottlenecks (e.g., u_{min}) and task completion delays (e.g., F_{min}) decreases problem difficulty. Therefore, the problem's difficulty is impacted most by the budget level and network's size.

Table 4.1: Solution characteristics of the test instances. Solution characteristics include: (a) % above $min(A_t)$ represents variations to the resource allocation budget, (b) Obj represents the objective function value, (c) CT% represents the average percentage of follow-on tasks completed, (d) RT (s) represents the run time in seconds, and (e) Gap% represents the percentage optimality gap reported.

Instance	% above $min(A_t)$	Obj	CT%	RT (s)	Gap%
		$T = 20$			
A_1	0.00%	18630	17.50%	256	0.00%
A_2	0.50%	8751	5.75%	11576.54	3.96%
A_3	1.00%	8685	5.75%	12591.70	3.95%
A_4	5.00%	8388	4.88%	24491.82	3.95%
A_5	10.00%	8195	4.25%	16995.02	4.01%
A_6	25.00%	7955	4.38%	19813.11	3.99%
A_7	1000.00%	7750	4.25%	5730.91	3.80%
D_1	0.00%	18630	17.50%	256	0.00%
D_2	0.50%	8584	5.75%	18577.51	3.98%
D_3	1.00%	8539	5.63%	84947.76	3.88%
D_4	5.00%	8246	5.50%	73496.41	3.96%
D_5	10.00%	8048	5.00%	49942.34	3.96%
D_6	25.00%	7828	4.88%	56060.31	4.00%
D_7	1000.00%	7722	4.50%	50878.48	4.01%
D_2^*	0.50%	8598	5.75%	14200.79	3.64%
D_3^*	1.00%	8550	5.63%	20773.80	4.00%
D_4^*	5.00%	8254	5.50%	24506.75	3.99%
D_5^*	10.00%	8027	5.00%	41911.18	3.72%
D_6^*	25.00%	7795	4.88%	14045.59	3.90%
D_7^*	1000.00%	7758	4.50%	18160.41	4.06%
B_{min}	1000.00%	8667	8.75%	1061.40	0.03%
$u_{min}/F_{min}/B_{max}$	1000.00%	7737	4.25%	7200.00	3.53%
F_{max}	1000.00%	11276	5.75%	14531.81	0.23%
u_{max}	1000.00%	6829	2.38%	267.36	0.00%
		$T = 30$			
A_1^*	0.00%	27945	17.50%	256	0.00%
A_{01}^*	0.10%	12618	6.00%	32338.83	4.00%
A_{02}^*	0.20%	12408	5.75%	32852.13	3.77%
A_{03}^*	0.30%	12249	5.75%	49266.89	3.94%
A_{04}^*	0.40%	12184	5.75%	45163.66	4.00%

4.3 COMPUTATIONAL ANALYSIS: ADDRESSING THE CASE STUDY QUESTIONS

The case study results address the Section 1 case study questions through analysis of the test instances introduced in Section 4.2. Due to the heightened impact of decisions made during summer seasons (see Section 4.1 and Appendix B), the analysis only considers summer time periods. However, overall trends are indicative of the response in winter time periods.

Results are discussed in the following sections. Section 4.3.1 analyzes the base network budget instances (e.g., instances $A_1 - A_7$) to examine how the resource allocation budget impacts weighted response times. Section 4.3.2 further analyzes the base network budget instances to examine the stockpile configurations in relation to the resource allocation budget. Section 4.3.3 examines the infrastructure investments made in order to support the stockpile configuration decisions in Section 4.3.2. Section 4.3.4 explores impacts on the base network budget instances due to: resource deployment bottlenecks (e.g., instances u_{min}, u_{max}); delayed safety task completion time (F_{min}, F_{max}); and the tasks completed given the decisions made by the base network budget instances in previous sections. Finally, Section 4.3.5 examines the impacts resulting from enhancing the response network with the addition of four limited-capability sites (e.g., instances $D_1 - D_7$).

4.3.1 BUDGET VS. WEIGHTED RESPONSE TIMES

CS1: What are the impacts on response times of budgetary limitations? Budgetary limitations impact the level to which response times are reduced, and the number of time periods required to attain the best response. Figure 4.2 shows that early budget increases–of up to 10%–markedly impact oil spill response time. Indeed, a 53.03% improvement in the total weighted response time for the 0% budget level (A_1) is attained by budget instance A_2, or 0.5% above the level to maintain the initial stockpile. A similar improvement is also observed for the solution to the reduced-infrastructure budget instance, B_{min}, compared with instance A_1 (53.48%). The figure also demonstrates that significant improvements to each incident's response times are attained in Summer 3 (S3) and S5 at each budget level above A_1. Taken together, these observations indicate that a significant improvement to oil spill response times might only require relatively small stockpile and infrastructure investments.

Figure 4.2 demonstrates that improvements to the budget reduce the number of time periods required until each instance can reach a best possible response (e.g., 514), which is represented by the best summer response time to the uncapacitated budget instance A_7. All budget levels approach this best possible solution with a response time of under 575 by Summer S3 from a starting point of

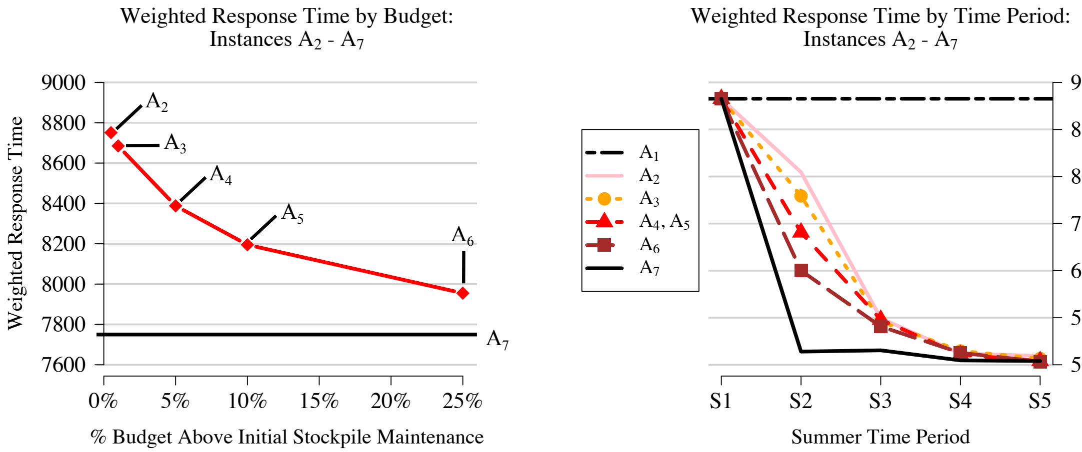

Figure 4.2: *Left:* Weighted response times by non-zero budget level for the original network instances (e.g., $A_2 - A_6$). The minimum value reported for the uncapacitated instance is displayed for reference as the best possible solution. Budget instance A_1 (solution: 18630) is omitted for clarity. *Right:* Weighted response times for the first five Summer time periods for the original network instances. Note that 5% and 10% solutions overlap in this figure despite differences in their solutions.

924, and each instance attains the best solution by S5. However, improved response times are largest for earlier rounds of investment, and budget levels above 25% provide less returns on investment. Therefore, diminished returns on investment are observable, in terms of improved weighted response times, as the resource allocation budget is increased. Decision-makers should take into consideration how diminishing returns on investments to improve oil spill response times can impact long-term plans to improve an Arctic response network.

4.3.2 STOCKPILE INVESTMENTS

CS2: How does geographic position within the response network influence the scale and scope of a stockpile? The impact of response site geographic position on the solution depends on the resource allocation budget, and, potentially, whether the site is centrally located. Table 4.2 demonstrates that the total number of resources stockpiled at each site can fluctuate over time at each budget level, eventually resulting in the amounts necessary to sustain the steady state solution (e.g., by Summer S5). Within these totals, certain resource types are stockpiled particularly early, such as boom and offshore vessels, which reflects their importance early in the response time horizon. Stockpile trends at Wainwright, the remote Chukchi primary response site, demonstrate this trend for sea- and land-based resources and vessel-based recovery equipment, necessary for most recovery task strategies (Section 4.1.4). These trends indicate that Anchorage, Dutch Harbor, and Deadhorse supply more of these resources to Wainwright at lower budget levels than at higher levels, in order to improve the early stages of a response in that region. Fairbanks and Barrow stock less equipment early in the time horizon, including boom, skimmers, and vehicles, but these amounts increase with the budget. Stockpiling decisions thus split resource amounts between response sites at different budget levels, addressing changing needs for resources over the response timeline. Taken in line with the results from Section 4.3.1, decision-makers can see the impact and importance of early budget increases on response time, and on the need for budget increases to improve stockpile configurations at different (remote) response sites earlier in the response. These results give insight into the site- and location-specific impacts of budget allocations over time.

Centrality within a response network refers to the degree to which a response site is positioned equidistant to all potential spill incident locations. Response sites that are more central have a maximum transit time to any one incident location that is similar to the average transit time to all incident locations, a consideration for decision-makers planning a response for multiple potential incidents. Stockpiling decisions at Barrow can provide insight into the significance of site centrality within the network.

The stockpile at Barrow, positioned between the primary response sites in the Beaufort region (e.g., Deadhorse) and Chukchi region (e.g., Wainwright), is improved early in the time horizon but receives smaller stockpile increases compared to Wainwright, especially at the lowest budget levels. Given that the stockpile at Deadhorse is typically reduced, due to the significant oil spill response capability of that site, the improvements at Barrow suggest that its stockpile is increased in order to serve the Chukchi region. These observations demonstrate that improving Barrow's stockpile, despite its central location between the Chukchi and Beaufort primary response sites, is not as important as improving Wainwright's stockpile, because of Wainwright's role as the Chukchi region primary response site and the need to improve incident response in that region. Decision-makers now have visibility of the timing and tradeoffs between and among response sites over the course of the response time horizon.

The observations in this section indicate that centrality in a response network, assumed to be a desirable quality, has a temporal characteristic: early in the response, for critical response tasks, centrality of a response site plays a less-important role in mobilizing the pre-staged resources that are available immediately. Once response supply chains are energized, centrality plays a more important role in improving response times.

Table 4.2: Resource stockpiles at each site in the Beaufort ($Zone_{BF}$) and Chukchi ($Zone_{CH}$) zones, averaged across the Summer time periods featuring stockpile improvements up to the steady state solution (e.g., S2 - S5). Values displayed are for the non-zero budget instances for the original network (e.g., $A_2 - A_7$).

			A_2				A_3			
Site	$Zone_{BF}$	$Zone_{CH}$	$S2$	$S3$	$S4$	$S5$	$S2$	$S3$	$S4$	$S5$
Anchorage	**5**	**5**	**592**	**494**	**414**	**607**	**594**	**494**	**730**	**608**
Dutch Harbor	5	5	158	86	45	2	158	101	54	54
Kodiak	5	5	89	74	77	57	87	75	40	99
Deadhorse	**1**	**3**	**562**	**581**	**734**	**529**	**571**	**579**	**359**	**319**
Fairbanks	5	5	0	67	8	109	0	59	185	247
Wainwright	**4**	**1**	**15**	**143**	**157**	**212**	**50**	**41**	**124**	**186**
Barrow	3	2	22	56	95	80	11	141	67	95
Kaktovik	2	4	0	8	6	50	0	3	0	25

			A_4				A_5			
Site	$Zone_{BF}$	$Zone_{CH}$	$S2$	$S3$	$S4$	$S5$	$S2$	$S3$	$S4$	$S5$
Anchorage	**5**	**5**	**556**	**520**	**759**	**611**	**531**	**512**	**718**	**680**
Dutch Harbor	5	5	101	86	15	166	101	68	38	1
Kodiak	5	5	85	53	3	186	88	99	98	106
Deadhorse	**1**	**3**	**584**	**587**	**469**	**284**	**577**	**593**	**409**	**326**
Fairbanks	5	5	0	98	20	38	1	112	104	40
Wainwright	**4**	**1**	**122**	**109**	**209**	**207**	**118**	**111**	**127**	**257**
Barrow	3	2	11	53	69	90	19	48	65	85
Kaktovik	2	4	2	27	0	0	6	0	0	97

			A_6				A_7			
Site	$Zone_{BF}$	$Zone_{CH}$	$S2$	$S3$	$S4$	$S5$	$S2$	$S3$	$S4$	$S5$
Anchorage	**5**	**5**	**520**	**518**	**700**	**719**	**499**	**497**	**418**	**596**
Dutch Harbor	5	5	97	84	74	64	132	52	144	198
Kodiak	5	5	83	66	148	142	83	36	174	23
Deadhorse	**1**	**3**	**559**	**535**	**309**	**314**	**262**	**318**	**288**	**288**
Fairbanks	5	5	88	137	119	128	41	54	151	161
Wainwright	**4**	**1**	**91**	**113**	**165**	**195**	**205**	**416**	**282**	**238**
Barrow	3	2	17	65	78	193	318	162	128	115
Kaktovik	2	4	31	55	84	0	71	85	121	87

CS3: What is the optimal stockpile improvement policy? The optimal stockpile improvement policy is impacted by the demands of each potential spill incident as defined by the case study setting, and by the extent to which a site is utilized. The results indicate that response zone 5, including southern Alaska and sites outside the network, will likely provide a significant amount of resources (e.g., $\geq$40%) for incidents of catastrophic volume, as illustrated in Figure 4.3. Figure 4.3 highlights this for Chukchi Sea incidents, given that Deadhorse also provides significant support in that region. This observation also holds for the case of an unlimited budget (e.g., A_7), which

supersedes the intuitive assumption that the closest response sites might eventually stockpile to the point of self-reliance, i.e., Arctic oil spill response might always rely on response sites in the south, such as Anchorage, Kodiak, and Dutch Harbor, due to the limitations of the North Slope sites. This phenomena occurs because of *maximally utilizing* a North Slope site, which can occur due to the site's mobilization capacity (Section 3.2), or how many resources it can prepare for transport to the incident location per response time period s. For example, if the capacity for Wainwright is sufficiently small, then a deployment bottleneck could result at Wainwright and it would be more beneficial to relieve this bottleneck by mobilizing resources from another site. Therefore, this mobilization capacity prevents all resources from being sited at Wainwright (even with an unlimited budget), which reduces the need for infrastructure investments at the site. Under these conditions, Wainwright is considered 'maximally utilized,' and its stockpile would be similar across budget levels due to the bottleneck that is formed by its mobilization capacity.

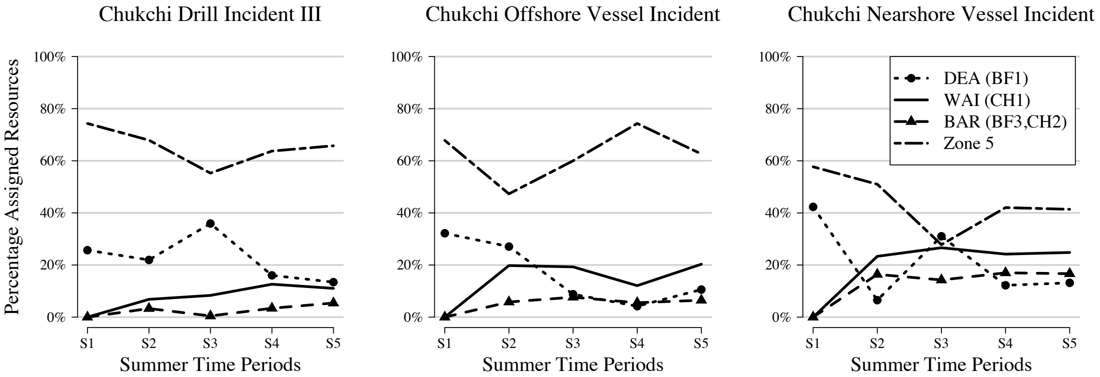

Figure 4.3: The percentage of resources that were mobilized for the Chukchi region incidents from key response sites during the summer time periods until the steady state solution (e.g., up to Summer $S5$) of the unlimited budget instance (e.g., A_7). The response sites (and associated response zones) include: Deadhorse (DEA), Wainwright (WAI), and Barrow (BAR). Kaktovik (e.g., response zones BF_2, CH_4) is omitted due to the negligible improvement afforded by the inclusion of that site.

The stockpiling trends in Table 4.2, considered with the trends to assign resources from response sites to Chukchi Sea incidents (e.g., Figure 4.3), indicate that maximal utilization impacts the primary sites (e.g., Wainwright in the Chukchi region, and Deadhorse in the Beaufort region), and the secondary site Barrow, but not Kaktovik. In the table, the trend is observed to 'level off' the stockpiles in Wainwright and Barrow once the steady state solution is reached (e.g., by Summer S5). In the figure, this trend is represented by the flattened resource assignment levels as the budget is increased. Figure 4.3 demonstrates that the Chukchi region exhibits greater reliance on distant support, and that Deadhorse can play a significant role in the response to an incident in this region. Barrow also plays an important role in the response for the Chukchi region; for example, Barrow assigns almost the same amount of resources to the Chukchi Nearshore Vessel Incident as Wainwright. These observations indicate that, although maximal utilization is a significant factor for Arctic response sites, its effects could be reduced by stockpiling resources at Barrow and Deadhorse in order to support Wainwright. This reveals a type of coordination between the response sites, determined by the role each site plays in mobilizing resources for each specific incident, which should be examined by decision-makers considering mobilization-limited response sites in the Arctic and similar regions. Regardless, the observed maximal utilization reveals that stockpiling every type of resource - and improving all associated infrastructures - at the response sites closest to the potential incidents of greatest concern is not necessarily the best policy in the Arctic.

4.3.3 INFRASTRUCTURE INVESTMENTS

CS4: What is the optimal infrastructure investment policy? The optimal infrastructure investment policy is impacted by budget level, and there exists a trend to the infrastructure investments made at each response site for resource allocation budget levels below A_7. Table 4.3 displays the earliest Summer time periods selected to invest in both infrastructure classes, the capability class (CB_x) and the capacity class (CP_x). The trend is observed to improve Wainwright earlier and to a greater degree than Barrow.

Wainwright improves nearshore-vessel siting capability and refueling capability (e.g., CB_1, CB_3) at lower budget levels, and improves offshore-vessel siting capability (e.g., CB_2) at higher budget levels. At budget levels below A_7, Barrow improves more affordable and more general capacity options, such as conex containers (e.g., CP_1) and gravel pads (e.g., CP_2), along with the refueling capability option (CB_1). These investments in more affordable infrastructure options confirm the earlier claim that relatively modest budget investments can significantly improve weighted response times (Section 4.3.1). Thus, infrastructure investments in Barrow are focused on stockpiling resources that serve supporting roles for Wainwright and the incidents in the Chukchi region, regardless of budget level. Combined with the results from the previous section, these observations reveal the coordination strategy that develops sites in a specific order, which ultimately promotes each site's role within a response effort. Analysis of the infrastructure budget instances (e.g., B_{min}, B_{max}) indicates that improving sites located toward the center of the network (e.g., sites Fairbanks, Barrow) can be beneficial when the sites closest to the incidents are mobilization limited. These central sites can improve their infrastructures quickly and operate as smaller stockpile hubs when this budget

Table 4.3: Summer time periods of the first infrastructure investments (e.g., S1 - S5) for response sites initially lacking infrastructure in the Arctic, by class: capability (CB_x), and capacity (CP_x). Values shown are for budget instances $A_2 - A_4$ and A_7 for emphasis. Time periods occurring after the steady state solution has been attained (e.g., Summer S6 and beyond) are represented by "S6+".

	A_2				A_3			
Site	CB_1	CB_2	CB_3	CB_4	CB_1	CB_2	CB_3	CB_4
Wainwright	S1	S2	S1	S3	S1	S2	S1	S2
Barrow	S3	S6+	S1	S3	S4	S3	S1	S3
Kaktovik	S6+	S6+	S6+	S6+	S6+	S6+	S6+	S6+
Site	CP_1	CP_2	CP_3	CP_4	CP_1	CP_2	CP_3	CP_4
Wainwright	S1	S1	S6+	S6+	S1	S1	S6+	S6+
Barrow	S2	S2	S6+	S6+	S1	S3	S6+	S6+
Kaktovik	S3	S6+	S6+	S6+	S2	S6+	S6+	S6+
	A_4				A_7			
Site	CB_1	CB_2	CB_3	CB_4	CB_1	CB_2	CB_3	CB_4
Wainwright	S2	S1	S1	S3	S1	S1	S1	S1
Barrow	S3	S5	S2	S2	S1	S2	S1	S1
Kaktovik	S6+	S6+	S6+	S6+	S2	S1	S1	S1
Site	CP_1	CP_2	CP_3	CP_4	CP_1	CP_2	CP_3	CP_4
Wainwright	S1	S2	S6+	S6+	S1	S1	S6+	S1
Barrow	S1	S2	S6+	S6+	S1	S1	S6+	S6+
Kaktovik	S1	S6+	S6+	S6+	S1	S1	S6+	S6+

is unconstrained, which demonstrates that coordination between response sites is beneficial at any infrastructure budget level.

4.3.4 TASK SCHEDULES

CS5: How do bottlenecks and delayed resource deployments inform the solution? Sources of bottlenecks, caused by the delayed completion of the safety task (e.g., F_{min}, F_{max}), and the resource mobilization capacity (e.g., u_{min}, u_{max}), present factors for decision-makers to consider prior to making infrastructure investment and resource stockpiling decisions.

Delayed safety task completion results in a non-intuitive infrastructure investment pattern, which is similar to that of the best possible solution in terms of prioritizing improvement for less-critical sites (e.g., Kaktovik, Fairbanks, and Dutch Harbor). In this case, the lag associated with delayed task completions "pushes" the primary sites out of their response zones (e.g., zones BF_1, CH_1), and into the more distant zones instead, negating the benefit from stockpiling where the resource transit times are the least. Therefore, if the safety task is delayed, then improvements to the response sites closest to the incidents might not be worthwhile, given that resources could arrive from farther away - and thus at reduced infrastructure expense - and be ready for deployment immediately after the safety task. Decision-makers considering infrastructure investments for Arctic response sites should first weigh the investment costs against the potential for factors to arise which could cause significant delays to the response, resulting in reduced returns on these investments. Visibility of the tradeoffs between investment costs and response delay costs are new decision support capabilities for Arctic oil spill response decision-makers.

Analysis of the resource deployment instances support these observations, indicating that even the best response relies on infrastructure improved at sites positioned farther away from the incidents in later time periods. If each site's mobilization capacity is not a limiting factor, then significantly reduced response times are attainable (Table 4.1), and decision-makers should examine potential causes that could reduce resource mobilization capacity at current and future response sites.

CS6: What are optimal task completion policies? The stockpile and infrastructure investment decisions, discussed previously, impact the priority to complete each task strategy and the type of response site selected for each task. Six task strategies are considered (Section 4.1): the safety task, mechanical recovery, in-situ burning, dispersants application, logistics, and spill tracking.

Two of the spill volume recovery strategies, mechanical recovery and in-situ burning, are responsible for addressing the majority of the spill volume (97%). Completion of these types of tasks is prioritized at the primary response sites (e.g., Wainwright and Deadhorse), regardless of resource mobilization capacity. Barrow's role as a support site for Chukchi incidents is identified: although it is observed to occasionally complete mechanical recovery tasks, this site generally completes tasks pertaining to spill tracking, the safety task, and logistics. Dispersants application, the remaining spill volume recovery strategy that is responsible for addressing the final 3% of the total volume, is prioritized at secondary sites in the more distant zones. Thus, the coordination strategy, discussed previously, impacts the types of tasks completed for each incident by each response site. In general, the strategy reduces the percentage of follow-on tasks that are completed for all incidents as factors constraining the response are diminished (Table 4.1), by decreasing the number of these tasks being completed from sites closest to the incident locations.

4.3.5 ENHANCED NETWORK

CS7: How does the inclusion of additional response sites impact the solution? The stockpile budget variation analysis is examined for the case of an enhanced response network that includes four additional, limited-capability, unmanned *storage sites* (e.g., budget instances $D_1 - D_7$).

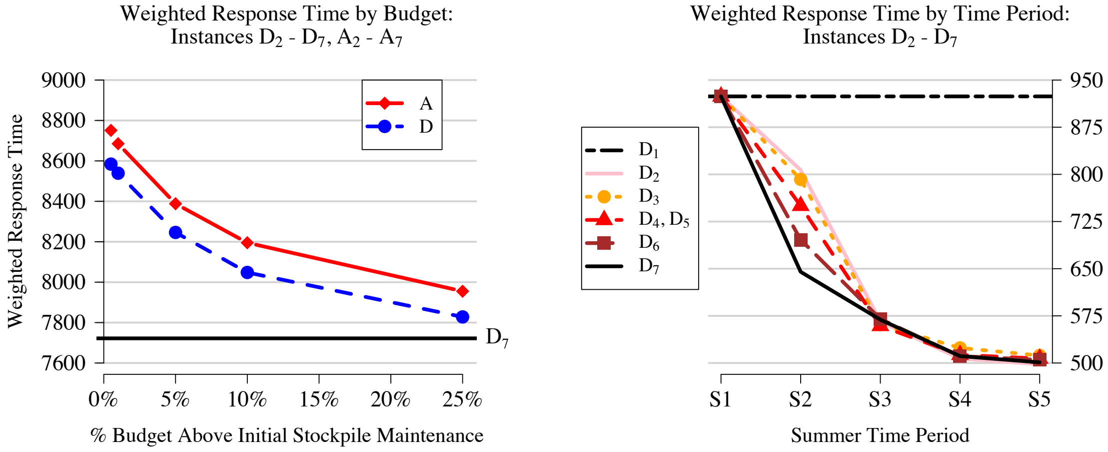

Figure 4.4: *Left:* Weighted response times by non-zero budget level for the enhanced network instances (e.g., $D_2 - D_7$) compared to the original network instances (e.g., $A_2 - A_6$). Budget instance D_1 (solution: 18630) is omitted for clarity. *Right:* Weighted response times for the first five Summer time periods for the enhanced network instances. Note that 5% and 10% solutions overlap in this figure despite differences in their solutions.

Figure 4.4 demonstrates that the improvements to weighted response times as the resource allocation budget is increased are similar to the improvements observed for the base network (e.g., budget instances $A_1 - A_7$). The improvements to the weighted response times are 2% on average, but attained at a five-fold increase in maintenance and infrastructure investment costs to stockpile (land-based) resources at these sites. The DEW Line sites primarily stockpiled resources for use within the Chukchi response zone, for the strategies of safety (TS_1), mechanical recovery (TS_2), and logistics (TS_5). Although these stockpiling decisions resulted in reduced support from the more distant zones (e.g., $BF2, BF3, CH2, CH3$), the most distant zones ($BF5, CH5$) display an increase in mobilized resources for most incidents in both regions, which indicates a reduced need to stockpile centrally within the response network. All of the observations in this section are undermined by the increased burden of refurbishing and maintaining the DEW Line sites, the political challenges that might exist, and the elevated risk of theft of equipment stockpiled within unmanned storage sites (as noted by domain experts). Decision-makers should consider these factors prior to selecting unmanned storage sites for inclusion within the Arctic response network, particularly from the DEW Line system.

5. CONCLUSIONS AND FUTURE WORK

This thesis proposed a novel dynamic network expansion problem that can be applied to a remote oil spill response (OSR) network. The model, its assumptions, and data requirements were assessed by subject matter experts in the U.S. Coast Guard and a major Oil Spill Response Organization in the context of OSR logistics to support energy exploration initiatives in the U.S. Arctic. Computational analyses were developed to derive policy insights pertaining to infrastructure investment decisions that the U.S. government could implement in order to improve OSR response times in this region. Together, the findings provide empirical support for the often-heard adage that early response deployment and budget increases have the greatest positive impact on improved response times, and by extension, on response effectiveness. Most importantly, however, decision-makers now have modeling and trade-off visibility for timing, budget, and resource allocation 'tipping points,' the points after which additional budget and resources have lower marginal benefits. Decision-makers in the Arctic and similar remote regions now have the capability to examine consequences of missed deadlines in terms of needing to complete a different response task to mitigate the impact of a missed deadline. Finally, the order in which effective coordination activities between oil spill response sites occur can now also be visualized. The visibility of tradeoff, timing, and cross-over points are new decision support capabilities for Arctic oil spill response decision-makers.

Relatively inexpensive stockpile and infrastructure investments to the present-day network could result in significant improvements to weighted response times. However, there may exist a point at which the gains resulting from investments are only marginal, indicating that certain sites' capabilities and any process that can delay deployments are conditions which limit the system in ways that are not purely economic. Conditions that limit a site's maximal utilization, such as insufficient personnel or physical access to an incident, and those contributing to response delays, such as completion of human safety tasks or government permit-approval processes for other tasks, can result in reduced returns on investment for improvements made to the most remote response sites. Decision-makers might test for the presence and severity of these conditions in order to assess the capability of remote response networks and promote cost-effective solutions.

Stockpile and infrastructure decisions should promote the completion of critical, time-consuming tasks by mobilizing and deploying resources from remote response sites which are closest to areas of elevated risk of an oil spill incident. These sites can work in conjunction with neighbors within nearby response zones in order to overcome limitations present in the system, by stockpiling resources for certain, different tasks in each site. Sites are preferred based on their ability to handle specific roles rather than how central they are in the response network. Centrality of response sites within the response network has a temporal quality: centrality is less important early in the response and becomes more important as supply chains become energized.

Coordination strategies between response sites mobilizing oil spill response resources have a particular role in oil spill response, as they reduce the percentage of follow-on tasks required. Cooperative behavior, in terms of sharing and shipping resources between response sites, should be further explored, to develop empirical support and modeling capability for international oil spill response cooperation.

The inclusion of unmanned storage locations by way of refurbished DEW Line sites could provide small improvements to incident response times, but at significant cost. Decision-makers should consider whether remote storage locations, and perhaps the DEW Line in particular, are cost effective measures to improve the response network.

This work should be extended so that modeling remote OSR networks can be applicable to a wider variety of settings. One extension should consider the impacts due to uncertainty in resource transit times, on-hand resources, safety task completion time, and task deadlines. Examination of these uncertainties could yield task completion policies that incorporate climatological factors in order to provide a framework for organizing response operations under a variety of real-world circumstances. This extension could also explore factors influencing the task weights, or new objective function formulations that model different definitions of weighted response times. Another extension should consider how multinational operators can work in tandem to develop an international response network and task completion policies that are impacted by the constituent member states. For instance, it could be important to examine situations where United States and Canada respond jointly to oil spill incidents in the Beaufort Sea. Algorithmic and/or heuristic development should be explored for problems of increased complexity and size in order to reduce the difficulty and yield quality solutions in a reasonable time frame.

An extension of this work is underway in order to explore the development of a model for use with the assessment of Oil Spill Response Plans (OSRPs) by government agencies, which provide detailed plans concerning the risk factors surrounding a potential spill incident and the response measures that are likely to be utilized for that specific incident (Royal Dutch Shell PLC, 2015). An OSRP makes logistical details known regarding resource types and locations in support of the planned response measures (Royal Dutch Shell PLC, 2015). Thus, for an assessment, resource allocation decisions are assumed to be fixed, and a plan for the improvement of infrastructures and adjustment of the resource stockpiles over time is not necessarily required. Decision makers could benefit from the ability to gauge the timing and method with which resources might converge at the incident, subject to additional salient features surrounding the response tasks scheduling problem as discussed within an OSRP. Therefore, an extension of the spill response constraints within a stand-alone model might be suitable for use with the assessment of OSRPs. As part of the Systems Development and Life Cycle process, a draft of the data and model requirements determination processes for this spill response model is presented in Appendix C.

Review of OSRPs and subject matter expert interviews have revealed the need to extend the spill response constraints via four enhancements: (i) incorporating tasks undergoing completion beyond the equipment deployment phase; (ii) explicitly accounting for manpower; (iii) guaranteeing sufficient recovered waste storage capacity; and (iv) altering the task deadline model logic so that the follow-on consequences from a missed deadline are dependent on the amount of oil remaining in the water by that time. These four enhancements will allow the stand-alone spill response model to provide a more detailed schedule of response tasks and provide decision support opportunities pertaining to a sustained response effort.

The spill response constraints generate a schedule of tasks for the periods of time until equipment has been deployed at a spill incident. However, the assessment of an OSRP would require a task schedule which includes the activities post-deployment, in order to determine the robustness of a sustained potential response effort (Royal Dutch Shell PLC, 2015). For instance, an OSRP for a drill blowout in the Chukchi Sea in July might require six oil spill response vessels in order to rapidly treat and recover the entire estimated spill volume for the duration of the response time horizon. In this example, use of these vessels might be staggered over time, so that four can recover waste while two offload waste into storage.

Manpower is not explicitly considered by the spill response constraints; however, for the assessment of an OSRP, manpower would constrain the problem by requiring that sufficient response personnel are available at response sites prior to the deployment of resources for each task. Once deployed, personnel are required to assist with the completion of each task for the remainder of the response time horizon (Alaska Clean Seas, 2012; Royal Dutch Shell PLC, 2015). The available manpower can fluctuate over time, and potentially increase, due to: (i) the need for certain resources to require additional personnel up to the time of deployment, which would allow those personnel to become available for other tasks after that point in time (Alaska Clean Seas, 2012); and (ii) the use of mobile encampments to increase the available manpower at a specific response site for the duration of the time horizon (Royal Dutch Shell PLC, 2015).

The requirement of sufficient recovered waste storage capacity at each time period of the response time horizon is not modeled by the spill response constraints, but would be required for the assessment of an OSRP (Royal Dutch Shell PLC, 2015). Additionally, oil spill recovery resources are rated for the speed with which they can collect liquid waste from the spill incident (Alaska Clean Seas, 2012; Royal Dutch Shell PLC, 2015), and these ratings allow decision makers to generate an expectation of the waste storage capacity requirements over time. For instance, the use of six oil spill response vessels might require the use of a tanker vessel in order to provide sufficient waste storage capacity for the duration of a response effort.

The spill response constraints model the follow-on consequences from a missed deadline based on whether a task was completed by a certain time period, which assumes that missing a task's deadline will directly result in a follow-on task. However, it was revealed that these consequences are more realistically modeled as the amount of oil remaining in the water by the deadline (Royal Dutch Shell PLC, 2015), which could be modeled as the selection of one follow-on task among an interval of follow-on tasks. In this way, the follow-on required for completion can be scaled by selecting from the interval the expected consequences from a portion of the spill volume remaining in the water and reaching the shore. Additionally, the spill volume might vary over time, which could result in unforseen impacts on the required follow-on tasks (U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region, 2015). For instance, if six recovery vessels are responding to a drill blowout and the deadline has past, then it might be reasonable to expect that a smaller portion of the spill volume remaining in the water will require a smaller shoreline cleanup operation compared with a larger portion remaining in the water at that time.

The U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement (BSEE) has examined the tasks and resource requirements for oil spill response in the Arctic, in order to develop standards and guidelines for the creation of OSRPs. Two publicly-available tools of note have been developed by BSEE to support the creation of OSRPs and may be incorporated into this work:

- The Western Response Resource List (WRRL): A repository of known oil spill response equipment stockpiles in the Pacific Northwest. Data stored within the WRRL could be utilized by the stand-alone spill response model, which would allow decision makers to generate task schedules that use equipment stockpiled across the Pacific Northwest. These schedules could also be updated as remote users login to the WRRL and revise the database; assuming the spill response model is housed in a separate facility, decision makers would have the means to rapidly and easily examine OSRPs under review (Genwest Systems, Inc., 2016b).

- Response System Planning Calculators: Tools utilized to estimate the potential performance of oil spill response equipment, as applied to mechanical recovery, in-situ burning, and dispersants response tasks. These calculators could be utilized in conjunction with the stand-alone spill response model in order to examine equipment performance given the start time of its associated task. For instance, if the spill response model schedules a mechanical recovery task at a specific time of the response time horizon, then a decision maker could use mechanical recovery planning calculator to estimate the equipment's performance given an estimate of the scenario's characteristics at that time. The planning calculators could also be used to verify the adequacy of a task schedule generated by the stand-alone spill response model (Genwest Systems, Inc., 2016a).

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APPENDIX A
MODEL

The complete model is presented in this appendix. Constraints 3.1-3.15 describe the oil spill response component decisions, and Constraints 3.16-3.23 describe the resource allocation component decisions. The remaining constraints define the variables. The model is formulated as

$$min \sum_{l \in L} \sum_{e \in E_t} \sum_{t \in T} w_{let} \tau_{let}.$$

subject to: (DMARA - OSR)

$$\begin{aligned}
\tau_{l_1 et} - d_{l_1 e} \pi_{l_1 et} &\leq 0 \text{ for } l_1 \in L, e \in E_t, t \in T \\
\tau_{l_2 et} - (d_{l_1 e} + 1)(1 - \pi_{l_1 et}) &\geq 0 \text{ for } (l_1, l_2) \in P, e \in E_t, t \in T \\
\sum_{j \in J} \chi_{ijl_1 et} - r_{il_1 et} \pi_{l_1 et} &\geq 0 \text{ for } i \in I, l_1 \in L, e \in E_t, t \in T \\
\sum_{j \in J} \chi_{ijl_2 et} - r_{il_2 et}(1 - \pi_{l_1 et}) &\geq 0 \text{ for } i \in I, (l_1, l_2) \in P, e \in E_t, t \in T \\
\chi_{ijlet} - r_{ilet} \zeta_{ijlet} &\leq 0 \text{ for } i \in I, j \in J, l \in L, e \in E_t, t \in T \\
\sum_{l \in L} \chi_{ijlet} - \Omega_{ijt} &\leq 0 \text{ for } i \in I, j \in J, e \in E_t, t \in T \\
\zeta_{ijlet} - \sum_{s \in S} \delta_{ijlest} &\leq 0 \text{ for } i \in I, j \in J, l \in L, e \in E_t, t \in T \\
(m_{ije} + n_{ilet}) \zeta_{ijlet} + \sum_{s \in S} (s-1) * \delta_{ijlest} - \sum_{s \in S} s \Delta_{lest} &\leq 0 \\
&\text{for } i \in I, j \in J, l \in L, e \in E_t, t \in T, \\
\tau_{let} - \sum_{s \in S} s \Delta_{lest} &\geq 0 \text{ for } l \in L, e \in E_t, t \in T \\
\sum_{s \in S} \Delta_{lest} &\leq 1 \text{ for } l \in L, e \in E_t, t \in T \\
\sum_{i \in I} \sum_{l \in L} \delta_{ijlest} - u_j &\leq 0 \text{ for } j \in J, e \in E_t, s \in S, t \in T \\
\sum_{l \in L} \sum_{s'=s}^{min(s+n_{ilet}-1, |S|)} g_{il} \Delta_{les't} - u_e &\leq 0 \text{ for } i \in I, e \in E_t, s \in S, t \in T \\
\Delta_{lest} - \nu_{e(d-n_{ilet})t} &\leq 0 \text{ for } l \in L \setminus \{f\}, e \in E_t, s \in S, t \in T \\
\nu_{est} - \Delta_{fest} - \nu_{e(d-1)t} &= 0 \text{ for } f \in L, e \in E_t, s \in S, t \in T
\end{aligned}$$

$$\begin{aligned}
\nu_{e1t} - \Delta_{le1t} &\leq 0 \text{ for } e \in E_t, 1 \in S, t \in T \\
\phi_{ij(t-1)} + \sum_{k \in J: k \neq j} \sigma_{ikj(t-1)} + \psi_{ij(t-1)} &= \Omega_{ijt} \text{ for } i \in I, j \in J, t \in T \\
\psi_{ijt} + \sum_{k \in J: k \neq j} \sigma_{ijkt} &= \Omega_{ijt} \text{ for } i \in I, j \in J, t \in T \\
\sum_{i \in I} \sum_{j \in J} \{a^1_{ijt}\phi_{ijt} + \sum_{k \in J: k \neq j} a^2_{ijkt}\sigma_{ikjt} + a^3_{ij}\psi_{ijt}\} &\leq A_t \text{ for } t \in T \\
\sum_{i \in I(o)} z_{io}\Omega_{ijt} - c_{jot}\lambda_{jot} &\leq 0 \text{ for } j \in J, o \in O^{CP}, t \in T \\
\lambda_{jo(t-1)} + \Lambda_{jo(t-1)} - \lambda_{jot} &= 0 \text{ for } j \in J, o \in O^{CP}, t \in T \\
\sum_{i \in I(o)} z_{io}\Omega_{ijt} - c_{jot}\alpha_{jot} &\leq 0 \text{ for } j \in J, o \in O^{CB}, t \in T \\
\alpha_{jo(t-1)} + \beta_{jo(t-1)} - \alpha_{jot} &= 0 \text{ for } j \in J, o \in O^{CB}, t \in T \\
\sum_{j \in J} \sum_{o \in O} b_{jot}(\beta_{jot} + \Lambda_{jot}) &\leq B_t \text{ for } t \in T
\end{aligned}$$

$$\begin{aligned}
\pi_{l_1 et} &\in \{0,1\} \text{ for } l_1 \in L, e \in E_t, t \in T \\
\tau_{let} &\geq 0 \text{ for } l \in L, e \in E_t, t \in T \\
\delta_{ijlest} &\in \{0,1\} \text{ for } i \in I, j \in J, l \in L, e \in E_t, s \in S, t \in T \\
\Delta_{lest} &\in \{0,1\} \text{ for } l \in L, e \in E_t, s \in S, t \in T \\
\varsigma_{ijlet} &\in \{0,1\} \text{ for } i \in I, j \in J, l \in L, e \in E_t, t \in T \\
\chi_{ijelt} &\geq 0 \text{ for } i \in I, j \in J, e \in E_t, l \in L, t \in T \\
\nu_{est} &\in \{0,1\} \text{ for } e \in E_t, s \in S, t \in T \\
\Omega_{ijt} &\geq 0 \text{ for } i \in I, j \in J, t \in T \\
\alpha_{jot} &\in \{0,1\} \text{ for } j \in J, o \in O, t \in T \\
\beta_{jot} &\in \{0,1\} \text{ for } j \in J, o \in O, t \in T \\
\lambda_{jot} &\geq 0 \text{ for } j \in J, o \in O, t \in T \\
\Lambda_{jot} &\geq 0 \text{ for } j \in J, o \in O, t \in T \\
\phi_{ijt} &\geq 0 \text{ for } i \in I, j \in J, t \in T \\
\sigma_{ijkt} &\geq 0 \text{ for } i \in I, j \in J, k \in J, t \in T \\
\psi_{ijt} &\geq 0 \text{ for } i \in I, j \in J, t \in T
\end{aligned}$$

APPENDIX B
CASE STUDY DETAILS

Details regarding the case study are presented in this appendix. Section 2.1 presents summary characteristics of the response network (Table B.1), and the dependencies between each of resource types and associated infrastructures utilized for stockpiling purposes (Table B.2). Section 2.2 discusses summary differences between the summer and winter seasons (Table B.3). Section 2.3 summarizes key descriptive characteristics of each modeled potential spill incident (Table B.4). Section 2.4 provides summary characteristics describing how the resource requirements were generated for each potential incident (Table B.5). Section 2.5 provides additional considerations and assumptions placed on the use of DEW Line sites for the enhanced network instances (Table B.6), and all other assumptions of the case study (Table B.7).

B.1 RESPONSE SITES

Table B.1 provides summary characteristics of the response network. Population sizes are included as proxies for existing infrastructure. The population for Deadhorse includes the transient workforce present for energy exploration operations in that region, and is officially far lower. Direct miles to Kodiak indicate the distances from the only significant USCG response site currently in Alaska. Each response site's role (e.g., hub, primary, secondary) impacts the time required to deploy resources at an incident site.

Table B.1: Response Network Characteristics

Name	Population Size	Kodiak Dist. (mi.)	Role
Anchorage	300,950	253	Hub
Dutch Harbor	4,319	610	Secondary
Kodiak	6,423	0	Secondary
Deadhorse	3,000*	866	Primary, Beaufort Region
Fairbanks	32,324	511	Secondary
Wainwright	579	916	Primary, Chukchi Region
Barrow	4,373	942	Secondary
Kaktovik	247	892	Secondary

Table B.2 presents the infrastructure dependencies modeled for the set of resources. Resources rely on an infrastructure type given the symbol "X". Infrastructure names are as follows: gravel pad (GP), conex container (CON), small aircraft hangar (HA1), large aircraft hangar (HA2), landing strip (LS), vehicle refueling depot (FUL), small vessel boat launch (BL1), large vessel boat launch and pier (BL2).

Table B.2: Infrastructure Dependencies

	Infrastructure Type							
Resource Type	GP	CON	HA1	HA2	LS	FUL	BL1	BL2
Small Aircraft	-	-	X	-	X	X	-	-
Large Aircraft	-	-	-	X	X	X	-	-
Offshore Boom	X	X	-	-	-	-	-	-
Near Shore Boom	X	X	-	-	-	-	-	-
In-Situ Burning Equipment	X	X	-	-	-	-	-	-
Dispersant	X	-	-	-	-	-	-	-
Mobile Facility	X	X	-	-	-	-	-	-
Near Shore Vessel	X	-	-	-	-	X	X	-
Offshore Vessel	-	-	-	-	-	X	-	X
Tank Vessel	-	-	-	-	-	X	-	-
Storage Bladder	X	-	-	-	-	-	-	-
Offshore Skimming Vessel	-	-	-	-	-	-	-	-
Skimmer System	X	X	-	-	-	-	-	-
Ground Vehicles	X	-	-	-	-	X	-	-

B.2 TEMPORAL CHARACTERISTICS

Table B.3 presents summary differences between the summer and winter seasons. Seasonal differences significantly impact the tasks required for a potential spill incident, along with the types and amounts of resources necessary for each task.

Table B.3: Summary Differences between the Seasons

(i) The presence of solid pack-ice at the spill incident during winter seasons requires the use of land-based resources, such as backhoes, to remove a section of the ice in order to contain and recover the spill volume (Alaska Clean Seas, 2012).
(ii) During winter seasons, the ice is thick enough to allow these resources to travel overland from a response site (Alaska Clean Seas, 2012), and expert interviews suggested that in some cases, a landing strip can be established on the ice close to the spill in order to hasten the arrival of additional equipment.

B.3 GENERATING POTENTIAL SPILL INCIDENTS

Table B.4 presents details regarding the spill incident characteristics. Spill incident characteristics include the incident source (DRL = drill, OSV = offshore vessel, NSV = near shore vessel), Arctic region, geographic coordinates, distance to shoreline in nautical miles (NM), and calculated response deadline in units of 6-hour periods.

Table B.4: Spill Incident Characteristics

Source	Region	Location	Shoreline Distance (NM)	Deadline
DRL	Beaufort	70°23’46.82"N, 146°01’03.46" W	27.8	24
OSV	Beaufort	71°2’46.53"N, 151°24’46.62" W	26.2	22
NSV	Beaufort	70°38’23.78"N, 151°18’9.62" W	17.5	15
DRL	Chukchi	71°10’24.03"N, 163°28’18.52" W	86.9	29
OSV	Chukchi	70°19’33.98"N, 163°55’0.28" W	39.1	13
NSV	Chukchi	70°9’32.35"N, 162°57’59.11" W	11.3	4

B.4 DETERMINING TASKS AND RESOURCES FOR A SPECIFIC SPILL INCIDENT

Table B.5 presents details regarding how the resource requirements for each spill incident were generated. A mapping was developed to generate the resource types and amounts required for each task of each incident. The mapping generates these amounts by requiring that the total volume spilled is answered by the recovery task strategies, subject to the lower bound efficiency level for each. U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region (2011a) provides these lower bounds on efficiency levels: (i) in-situ burning (90% efficient); (ii) dispersants (30% efficient); (iii) mechanical recovery (10% efficient). Industry feedback suggested scaling the resources for mechanical recovery by a factor of 7 to account for the difference in resource amounts remaining after each level was applied to each respective strategy in turn.

Table B.5: Spill Incident Resource Requirements

Name	Discharge Volume	Daily Rate	Vol. Burn.	Vol. Disp.	Vol. Mech. Recov’d
BF DRL I	0.048	0.048	0	0	0
BF DRL II	1.555	1.555	1.4	0.047	0.109
BF DRL III	480	16	14.4	0.48	1.12
BF NSV	12.5	12.5	11.25	0.375	0.875
BF OSV	12.5	12.5	11.25	0.375	0.875
CH DRL I	0.048	0.048	0	0	0
CH DRL II	1.555	1.555	1.4	0.047	0.109
CH DRL II	750	25	22.5	0.75	1.75
CH NSV	12.5	12.5	11.25	0.375	0.875
CH OSV	12.5	12.5	11.25	0.375	0.875

This mapping accounts for the low efficiency rating of mechanical recovery, in actuality the primary response strategy, by applying in-situ burning to the remainder of the spilled volume, as suggested during expert interviews and following oil spill response guidelines (e.g., Alaska Department of Environmental Conservation Science and Technology Committee (2010)). Additionally, the mapping treats the use of dispersants as a supplemental strategy by applying it to the least amount of spilled volume, given its potentially difficult implementation in this environmentally sensitive region (Alaska Department of Environmental Conservation Science and Technology Committee, 2010). The details presented in Table B.5 include: spill incident discharge volumes, daily rate of seepage required for response, and volume of daily seepage recovered by in-situ burning tactics, dispersant application, and mechanical recovery tactics. Volumes listed are in thousands of barrels.

B.5 ADDITIONAL CONSIDERATIONS AND ASSUMPTIONS

Table B.6 presents details regarding the use of DEW Line sites within the response network. The enhanced network instances include capability-limited sites which operate as unmanned *storage sites*, modeled as remote storage locations converted from installations within the Distant Early Warning Line (DEW Line) system of now-defunct radar installations (Lackenbauer, Farish, & Arthur-Lackenbauer, 2005), and located in the Chukchi Sea region response zones $CH1, CH2$. These sites were selected due to the significant difficulty and expense required to create new response sites within the region. Resource security and maintenance over the short- and long-term are notable issues that should be considered prior to making any DEW Line allocation decisions.

Table B.6: DEW Line Site Assumptions

(i) DEW Line sites are only capable of storing land-based resources.
(ii) DEW Line sites incur additional costs to store equipment and improve infrastructure.
(iii) DEW Line sites require additional transit time in order to acquire response equipment prior to deployment.

Table B.7 presents key assumptions placed on the case study. Several assumptions are made, based on the information collected from open sources and subject matter expert interviews, in order to discuss the research findings in a realistic setting by aligning the case study with certain publicly available documents (U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region, 2011b, 2011a; United States Coast Guard, 2013; Alaska Clean Seas, 2012). These assumptions help ensure that the resource allocation decisions are properly attributed to the U.S. government aspect of the response while also acknowledging that industry would supply a significant nearshore and offshore response fleet.

Table B.7: Key Assumptions

Assumption	Definition
(i)	Anchorage acts as a primary resource hub through which all regional Oil Spill Response Organizations (OSRO's) may transport resources to the primary response sites; this site always maintains the minimum stockpile required for feasibility.
(ii)	Dutch Harbor has the majority of sea-based resources initially stockpiled due to its significance as a regional fishing fleet hub.
(iii)	Kodiak has the resources initially stockpiled to answer the safety task due to its USCG presence.
(iv)	Deadhorse is a North Slope site with comparatively enhanced capability and infrastructure due to its location near the Beaufort Sea and the energy exploration projects that have developed in that region.
(v)	Fairbanks is centrally located within the state and has significant infrastructure and provides an overland connection between North Slopes sites and Anchorage.
(vi)	Barrow, Wainwright, and Kaktovik are North Slope sites with minimal response capability and little to no initial infrastructure and resources.
(vii)	Transit times are determined by the fastest possible transportation method (e.g., land, sea, and air), given that only certain sites may transport over land due to the lack of roadway infrastructure.
(viii)	Any offshore capability necessary for drill incidents is pre-staged local to any drill locations (U.S. Department of the Interior, Bureau of Ocean Energy Management Alaska OCS Region, 2011b, 2011a); this supplies 50% of the capability required for offshore vessel incidents given the inability to stockpile those resources otherwise.
(ix)	Costing information for resource allocation decisions was derived from USCG daily operating rates data, and infrastructure costs were approximated based on publicly available construction project and purchasing information.
(x)	14 generic resource types were selected by considering those most critical for deploying every task.
(xi)	8 infrastructure types were modeled as determined by the resource-infrastructure dependencies necessary to site the 14 resource types.
(xii)	Infrastructure investments are only made during periods of no ice presence.
(xiii)	Current resource stockpiles were estimated from a number of publicly available sources from the Alaska Department of Environmental Conservation, the U.S. Coast Guard, and major OSRO's operating in the region.
(xiv)	Spill volumes emanate from a source at a fixed, daily rate.
(xv)	The geographic coordinates for drilling in the region determined the distance from shore for drill incident types; those distances for vessel incidents were selected in coordination with subject matter experts.

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Table B.7 – continued from previous page

Assumption	Definition
(xvi)	Effectiveness ratings for each response tactic strategy: burning (90%); dispersants (30%); mechanical recovery (10%).
(xvii)	An incident must have at least one task completed.
(xviii)	Tasks for the Mechanical Recovery and In-Situ Burning strategies are the only ones that require follow-on tasks if a deadline is missed.
(xix)	The resource allocation time horizon T is defined as 10 years containing two seasons each, and task deployment horizon D is defined as 7 days containing four 6-hour periods each.

APPENDIX C
MODEL DEVELOPMENT AND THE SYSTEMS DEVELOPMENT LIFE CYCLE

This appendix provides a comprehensive list of the steps of the Systems Development Life Cycle (SDLC) phases (Centers for Medicare and Medicaid Services, 2005; Blanchard & Fabrycky, 2006; Post & Anderson, 2006; Pendharkara et al., 2008; Radack, 2009; Marakas & O'Brien, 2010; He et al., 2015)that occurred during model development, as introduced in Section 3.5. The first three phases of the SDLC process (e.g., Requirements Determination, Design, and Software Development) were undertaken during model development. Table C.1 provides an overview of these phases; note that phases in the table can overlap, as is common during the SDLC process (Blanchard & Fabrycky, 2006; Post & Anderson, 2006; He et al., 2015). The Requirements Determination phase of the SDLC process (e.g., August 2013 until December 2014) established the functionality of the model via briefings with the USCG early in the project. The Design phase (e.g., September 2013 to December 2014) involved the incorporation of critical feedback into the model. During the Software Development phase (e.g., December 2014 to April 2016), efforts to transition the model into a software package commenced, in order to provide decision-makers with a tool for assessing oil spill response plans, as discussed in Section 5.

The Requirements Determination phase (e.g., Phase I in the table) and the Design phase (e.g., Phase II) overlapped with one another during model development. During this time, project goals were established, model functionality was planned, and the model was developed and vetted along with a vetted case study dataset. The vetting process involved subject matter experts at the U.S. Coast Guard (USCG) and a major Oil Spill Response Organization (OSRO) operating in Alaska. The vetting process required the collection and integration of information from public sources, as well as from interviews with the experts. A review process occurred by the subject matter experts once information was collected and integrated, which generated critical feedback to be incorporated into the model. This process, which entailed five key domain expert meetings (M1 - M5 in the table) between 2013 - 2014, expanded on the effort to establish reasonable assumptions and modeling logic. Assumptions and data for use with the case study setting were also reviewed at these meetings.

Meeting M1 in November 2013 with the OSRO in Anchorage, AK, provided approval of the objective function (Section 3.1) and decisions pertaining to task deadlines and follow-on tasks (e.g., Constraints 3.1 - 3.10). The need to incorporate maintenance costs for holding equipment between resource allocation time periods was revealed to be significant (e.g., Constraints 3.16 - 3.18), given the need to replenish certain resource types and the frequency of theft of stockpiled resources.

Meeting M2 in July 2014 in Anchorage with the USCG and the OSRO introduced the concept of safety task completion prior to the deployment of other tasks. During this meeting, it was revealed that an officiating agency would first conduct human safety operations and determine whether the environment at the spill incident is sufficiently safe for response operations to commence (e.g., Constraints 3.13 - 3.15). For instance, safety operations for a drill blowout must be completed prior to the deployment of recovery tasks near the drilling platform, so that these operations are unimpeded by the presence of recovery vessels operating in the vicinity, and to ensure conditions around the platform are unlikely to put additional lives at risk.

Meeting M3 in September 2014 occurred during the Canada-U.S. Oil Spill Response Exercise in Juneau, AK. Important differences between two infrastructure design option classes were captured at this meeting: *capacity options*, which improve storage capacity for resources (e.g., Constraints 3.19, 3.20); and *capability options*, which allow for stockpiling resources (e.g., Constraints 3.21, 3.22). Differences in costs between the two classes were also considered at this meeting (e.g., Constraints 3.23). For instance, air-based capability can be introduced by constructing a landing strip and refueling depot (capability options), and a hangar (capacity option). This meeting also led to expanding the case study to analyze the use of DEW Line sites as unmanned storage sites within the response network (e.g., Section 4.3.5).

Meeting M4, a November 2014 conference call with the OSRO, explored: (i) the capacity of a response site to mobilize resources; and (ii) the capacity for tasks to be completed at a spill incident. The *resource mobilization capacity* is designed to reflect how environmental and personnel conditions at each site impact the number of resources that can be concurrently prepared for transport to the incident (e.g., Constraints 3.11). For instance, Anchorage might be more capable than Wainwright, given the differences in personnel housing levels, established roadways, and access to hospitable waterways. The *task completion capacity* is designed to reflect how conditions present at the spill incident impact the number of tasks that can be concurrently processed for completion (e.g., Constraints 3.12). For example, the use of several waste recovery vessels might require additional time to deploy at the incident in order to ensure effective coordination in rough seas.

Meeting M5 in December 2014 included a series of USCG briefings in Juneau, Anchorage, and Washington, D.C. During this meeting, clarification of certain assumptions and final approval for the case study setting were provided (e.g., Section 4.1). The model and data vetting process were discussed with the USCG, and the plan for conducting computational analyses was reviewed (e.g., Section 4.3).

During the Software Development phase (e.g., Phase III of the table), the process of developing the model into a decision aid began, in order to provide decision-makers with a tool for assessing oil spill response plans based on the spill response constraints of the model, as discussed in Section 5. The spill response constraints were considered within a stand-alone model, which would function as the decision support mechanism of a computerized decision aid. Members of the National Oceanic and Atmospheric Administration (NOAA) were involved with the development of a method to visualize the decision aid. Finally, a prototype of the decision aid was presented to the USCG, NOAA, and members of the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement. The requirements for this decision aid were also established during this phase, and a Requirements Document was developed, as discussed in Appendix D.

Table C.1: Subject Matter Expert Meetings

Date	SDLC Phase	Members	Summary
August 2013	Phase I	CDR Paul M. Stocklin (USCG) CAPT Jamie Robinson (USCG) Mark Everett (USCG) LT CDR Jason Boyle (USCG)	First conversation with USCG D17; established project goals; initial model and case study approval
September 2013	Phase I, Phase II	CAPT Jamie Robinson (USCG), Mark Everett (USCG)	Revised model approval including task scheduling logic; addressed case study questions
November 2013	Phase I, Phase II	Lee Majors	(Meeting M1) First conversation with Lee Majors; vetted objective function, and task deadlines and follow-on task model logic; initial data gathering
February 2014	Phase I, Phase II	CDR Paul M. Stocklin (USCG) CAPT Jamie Robinson (USCG) Mark Everett (USCG) Mike Lehocky (USCG) Christine Hansen (USCG)	Initial model complexity and case study results
July 2014	Phase I, Phase II	CDR Paul M. Stocklin (USCG) CAPT Jamie Robinson (USCG) Mark Everett (USCG) Lee Majors (ACS) Chris Hall (ACS)	(Meeting M2) Safety task completion model logic; data gathering
August 2014	Phase II, Phase III	CAPT Jamie Robinson (USCG) Mark Everett (USCG)	Initial planning discussion for stand-alone spill response model for use with the assessment of OSRPs
September 2014	Phase I, Phase II	Lee Majors	(Meeting M3) Infrastructure design option model logic; data gathering

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Table C.1 – continued from previous page

Date	SDLC Phase	Members	Summary
September 2014	Phase I, Phase II	CDR Paul M. Stocklin (USCG) CAPT Jamie Robinson (USCG) Mark Everett (USCG) Mike Lehocky (USCG) Christine Hansen (USCG)	Review of model and case study
November 2014	Phase I, Phase II	Lee Majors	(Meeting M4) Resource mobilization and task completion capacities model logic; completion of data gathering and vetting process
December 2014	Phase I, Phase II, Phase III	CAPT Claudia Gelzer CAPT Julia Hein LT Sara Booth Thompson CDR Paul M. Stocklin (USCG) CAPT Jamie Robinson (USCG) Mark Everett (USCG) Mike Lehocky (USCG) Christine Hansen (USCG)	(Meeting M5) Review of final model and final case study setting
December 2014	Phase II, Phase III	Mark Everett (USCG)	Planning discussion of stand-alone spill response model for use with the assessment of OSRPs
February 2014	Phase II, Phase III	Mark Everett (USCG)	Established functionality of stand-alone spill response model for use with the assessment of OSRPs
March 2015	Phase II, Phase III	CDR Paul M. Stocklin (USCG) CAPT Jamie Robinson (USCG) Mark Everett (USCG) Mike Lehocky (USCG) Christine Hansen (USCG)	Presentation of model logic and data vetting process
November 2015	Phase II, Phase III	Amy Merten (NOAA)	Planning for visualization software for use with the decision aid
December 2015	Phase II, Phase III	Amy Merten (NOAA)	Identified visualization software for use with the decision aid
December 2015	Phase II, Phase III	CAPT Claudia Gelzer CAPT Julia Hein LT Sara Booth Thompson CDR Paul M. Stocklin (USCG) CAPT Jamie Robinson (USCG) Mark Everett (USCG) Mike Lehocky (USCG) Christine Hansen (USCG)	Presentation of case study results
January 2016	Phase III	Amy Merten (NOAA) Jay Coady (NOAA) Rob Wright (NOAA)	Development of visualization prototypes for the decision aid
March 2016	Phase III	Jay Coady (NOAA) Rob Wright (NOAA)	Development of visualization software for use with the decision aid
February 2016	Phase III	Lee Majors (ACS) CDR Paul M. Stocklin (USCG)	Feedback collection for prototype visualizations of the decision aid

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Date	SDLC Phase	Members	Summary
April 2016	Phase III	LCDR Wes James (USCG) CDR Paul M. Stocklin (USCG) Mark Everett (USCG) Mike Lehocky (USCG) Christine Hansen (USCG) Amy Merten (NOAA) Jay Coady (NOAA) Rob Wright (NOAA) Eric Miller (BSEE) Karen Stone (BSEE) Sharon Buffington (BSEE)	Presentation of prototype spill response decision aid to USCG, NOAA, BSEE

APPENDIX D
REQUIREMENTS DOCUMENT

This appendix presents a draft Requirements Document to develop this work into a decision aid for decision-makers concerned with assessing Oil Spill Response Plans in accordance with the Systems Development and Life Cycle (SDLC) process. The Requirements Document specifies the features which should be included within the decision aid, describes each feature, and provides the conversation with one or more domain experts that serves as the source of each feature. The decision aid is discussed in Section 5, and Sections 3.5,C present the SDLC process and the phases completed for the development of this decision aid.

Requirement Type	Description	Category	Requirement #	Operationalization	Test	Source	Date Added	Priority
System Level Requirements	Functions, characteristics, and constraints of the system	DMARA-OSR Decision Aid functions, characteristics, and constraints	**0.1.1**	The DMARA-OSR Decision Aid shall display the OSR equipment deployed over time.	System Demonstration	Phone conversation with Lee Majors (3/31/2016)	4/6/16	**High**
			0.1.2	The DMARA-OSR Decision Aid shall display the OSR tasks completed over time.	System Demonstration	Email conversation with Martha Grabowski (1/20/2016)	4/6/16	**High**
			0.1.3	The DMARA-OSR Decision Aid shall display where equipment was mobilized for all tasks over time.	System Demonstration	Email conversation with Martha Grabowski (1/20/2016)	4/6/16	**High**
			0.1.4	The DMARA-OSR Decision Aid shall gauge the impact of users' decisions.	System Demonstration	Email conversation with Martha Grabowski (1/20/2016)	4/6/16	**High**
			0.1.5	The DMARA-OSR Decision Aid shall display a performance metric of users' decisions.	System Demonstration	Phone conversation with Lee Majors (3/31/2016)	4/6/16	**High**
			0.1.6	The DMARA-OSR Decision Aid shall highlight OSR equipment mobilization bottlenecks.	Live Demonstration; System Test	Phone conversation with Jay Coady (3/31/2016)	4/6/16	**High**
			0.1.7	The DMARA-OSR Decision Aid shall highlight OSR task deployment delays.	Live Demonstration; System Test	Phone conversation with Jay Coady (3/31/2016)	4/6/16	**High**
			0.1.8	The DMARA-OSR Decision Aid shall permit what-if analysis of user decisions.	Live Demonstration; System Test	Phone conversation with Lee Majors (3/31/2016)	4/6/16	**High**
			0.1.9	The DMARA-OSR Decision Aid shall utilize ERMA as the primary display.	Live Demonstration; System Test	Phone conversation with Jay Coady (3/31/2016)	4/6/16	**High**
			0.1.10	The DMARA-OSR Decision Aid shall utilize a supplementary display.	Live Demonstration; System Test	Phone conversation with Jay Coady (3/31/2016)	4/6/16	**High**

Table D.1: SDLC Requirements Document Part 1.

Requirement Type	Description	Category	Requirement #	Operationalization	Test	Source	Date Added	Priority
Information Requirements	Data elements and use-cases for the data	DMARA-OSR Model Output	**1.1**	The DMARA-OSR Decision Aid shall utilize information generated from the DMARA-OSR model.	System Audit	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
		Visualizations	**1.2.1**	The DMARA-OSR Decision Aid shall support the use of graphics within ERMA.	System Demonstration	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
			1.2.2	The DMARA-OSR Decision Aid shall support the use of text within ERMA.	System Demonstration	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
			1.2.3	The DMARA-OSR Decision Aid shall support the use of graphics within the supplementary display.	System Demonstration	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
			1.2.4	The DMARA-OSR Decision Aid shall support the use of text within the supplementary display.	System Demonstration	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
		User Input	**1.3**	The DMARA-OSR Decision Aid shall require a record of the users' decisions.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**
Technical Requirements	Hardware, software, databases, and networking capabilities	Hardware Requirements	**2.1.1**	The DMARA-OSR Decision Aid shall require hardware that is capable of interacting with ERMA.	System Audit	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
			2.1.2	The DMARA-OSR Decision Aid shall require hardware that is capable of interacting with the supplementary display.	System Audit	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
			2.1.3	The DMARA-OSR Decision Aid shall require hardware that is capable of reading .csv files.	System Audit	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
			2.1.4	The DMARA-OSR Decision Aid shall require hardware that is capable of writing .csv files.	System Audit	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
			2.1.5	The DMARA-OSR Decision Aid shall require hardware that is capable of computing a performance metric.	System Audit	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**
			2.1.6	The DMARA-OSR Decision Aid shall require hardware that is capable of electronically transmitting .csv files.	System Audit	Email conversation with Amy Merten (1/6/2016)	4/6/16	**High**

Table D.2: SDLC Requirements Document Part 2.

Requirement Type	Description	Category	Requirement #	Operationalization	Test	Source	Date Added	Priority
Technical Requirements	Hardware, software, databases, and networking capabilities	Software Requirements	**2.2.1**	The DMARA-OSR Decision Aid shall require software that is capable of interacting with ERMA.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**
			2.2.2	The DMARA-OSR Decision Aid shall require software for inputting user decisions.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**
			2.2.3	The DMARA-OSR Decision Aid shall require software for storing user decisions.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**
			2.2.4	The DMARA-OSR Decision Aid shall require software for electronically transmitting user decisions.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**
			2.2.5	The DMARA-OSR Decision Aid shall require software that is capable of computing a performance metric of the user's decisions.	System Audit	Email conversation with Martha Grabowski (9/15/2015)	4/6/16	**High**
			2.2.6	The DMARA-OSR Decision Aid shall support the use of commercial off-the-shelf software.	System Audit	Teleconference with D17 (8/21/2013)	4/6/16	**High**
		Database Requirements	**2.3.1**	The DMARA-OSR Decision Aid shall store users' decisions within a .csv file.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**
			2.3.2	The DMARA-OSR Decision Aid database shall be maintained by the database administrator.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**
		Network Requirements	**2.4.1**	The DMARA-OSR Decision Aid shall require an active internet connection.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**
			2.4.2	The DMARA-OSR Decision Aid shall require electronic file transfers to NOAA computer systems.	System Audit	Research team meeting (4/1/2016)	4/6/16	**High**

Table D.3: SDLC Requirements Document Part 3.

Requirement Type	Description	Category	Requirement #	Operationalization	Test	Source	Date Added	Priority
Human Factors and Ergonomic Requirements	Interface between users and the system	Human Computer Interactions	**3.1.1**	The DMARA-OSR Decision Aid shall display the performance metric of user decisions computed by comparison against solutions generated by the DMARA-OSR model.	System Demonstration	Research team meeting (4/1/2016)	4/6/16	**High**
			3.1.2	The DMARA-OSR Decision Aid shall require user input through a supplementary display.	System Demonstration	Phone conversation with Jay Coady (3/31/2016)	4/6/16	**High**
			3.1.3	The DMARA-OSR Decision Aid shall display activities occuring at each response site of the OSR network.	System Demonstration	Phone conversation with Lee Majors (3/31/2016)	4/6/16	**High**
			3.1.4	The DMARA-OSR Decision Aid shall display the tasks required for the spill incident.	System Demonstration	Phone conversation with Lee Majors (3/31/2016)	4/6/16	**High**
			3.1.5	The DMARA-OSR Decision Aid shall display the equipment required for the spill incident.	System Demonstration	Phone conversation with Lee Majors (3/31/2016)	4/6/16	**High**
			3.1.6	The DMARA-OSR Decision Aid shall utilize a time slider to visualize the dynamic nature of the user's decisions.	System Demonstration	Phone conversation with Lee Majors (3/31/2016)	4/6/16	**High**
			3.1.7	The DMARA-OSR Decision Aid shall display the OSR task completion times at each time period.	System Demonstration	Phone conversation with Lee Majors (3/31/2016)	4/6/16	**High**
			3.1.8	The DMARA-OSR Decision Aid shall display causes of mobilization bottlenecks at response sites.	System Demonstration	Phone conversation with Bo Stocklin (4/6/2016)	4/6/16	**High**
			3.1.9	The DMARA-OSR Decision Aid shall display causes of deployment delays at the spill location.	System Demonstration	Phone conversation with Bo Stocklin (4/6/2016)	4/6/16	**High**

Table D.4: SDLC Requirements Document Part 4.