A Proposed Cost-benefit Analysis Model for Physical Form Analysis for a Futuristic Submarine Decision Support System

by

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Submitted to the System Design and Management Program in Partial
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Abstract

This thesis proposes a model for cost-benefit analysis for physical form selection of a decision support tool, primarily to support system acquisition decisions that need to be made early in the system life cycle. By bringing objective and subjective costs and benefits into the same model and prescribing a unique approach to determining system utility, this thesis demonstrates how the proposed model can be applied for objective evaluation of display interfaces for a decision support system.

The proposed model, which is applied to a proposed decision support system for submarine commanders managing multiple unmanned underwater vehicles, follows an integrated systems engineering approach by first determining function followed by form. A hybrid cognitive task analysis is used to determine function, and cost-benefit analysis is used to determine form. The hybrid cognitive task analysis is a method for determining functions of a futuristic system, and the proposed cost benefit model fills the gap for objective evaluation of form.

The cost-benefit analysis was not straightforward, as determining objective usability of the physical display interfaces is difficult since it is not feasible to design fully functional interfaces and accompanying software in the conceptual design phase of the systems engineering process. Thus, one of the novel contributions of this cost-benefit model is the ability to objectively compare user performance across displays using a representative functional task in a relatively simple experimental setting.

While the application of the proposed cost-benefit model is shown only for application to the submarine commander decision support interface, it can be easily adopted for other human-systems integration efforts where system acquisition decisions are involved. This would benefit decision makers and system integrators in effective resource allocation and useful system implementation in the conceptual design phase.

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List of Acronyms

Acronym	Meaning
ASW	Anti-submarine warfare
ASuW	Anti-surface ship warefare
AHP	Analytical Hierarchy Process
CBA	Cost-benefit Analysis
CO	Commanding Officer
CTA	Cognitive Task Analysis
DL	Decision Ladder
HAL	Humans and Automation Lab
ISR	Intelligence, Surveillance and Reconnaissance
IT	Information Technology
MAT	Mission Assistance Tool
SA	Situational Awareness
UUV	Unmanned Underwater Vehicle

1. Introduction

In current underwater warfare, submarines and Unmanned Underwater Vehicles, UUVs co-exist but currently work independently of each other. With technology advancements in the near future, submarines will be expected to control UUV operations, and possibly offload some of their high risk tasks to the UUVs. In addition, UUVs will increase the reach and capability of submarines. Currently, submarines operate only in isolation, and the mission commander in a current submarine is responsible only for operating the submarine. To transition from that role to a role where the mission commander controls the submarine as well the UUV operations, s/he would need additional decision support. This thesis investigates the design of a decision support tool for the submarine's mission commander for this UUV management task.

1.1 Motivation

The motivation for this research is twofold: 1) the need to support a submarine commander's decision making while overseeing the operations of multiple UUVs and 2) the development of a methodology that evaluates different devices objectively in the conceptual design stage. Concepts developed for these two themes will aid the U.S. Navy in its vision of futuristic submarine missions. It will also lay the framework for developing conceptual design recommendations for human-systems decision support integration efforts that could apply across the Department of Defense.

1.2 Proposed Scenario

In the proposed scenario, there is a submarine controlling multiple UUVs. All of them are operating in the same general body of water, and the submarine commander is in charge of both overseeing the submarine's operation as well as the UUV missions. In addition, the submarine commander is also responsible for the health and safety of both the submarine and the UUV's. To carry out all these tasks, the submarine commander needs a decision support tool, which will provide decision guidance and situation awareness. Since the submarine commander is always on the move, the decision support tool must be portable. Current submarine technology is not capable of supporting such tools. However, futuristic missions as proposed here will have advanced technology that will allow such a tool to be integrated into its system. Figure 1 shows a pictorial view of such a futuristic scenario. In this scenario, there is a submarine and multiple UUVs nearby it controlled and operated by the submarine. The UUVs are conducting intelligence, surveillance and reconnaissance (ISR), looking for underwater mines.

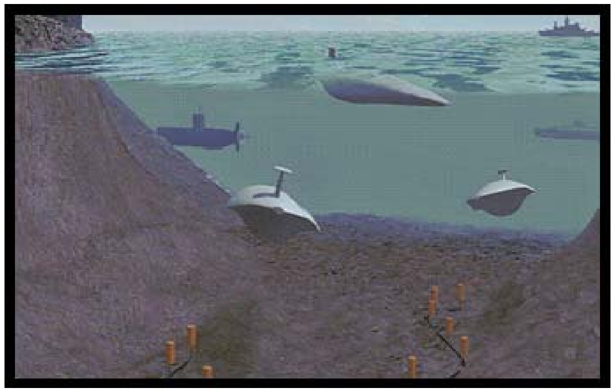


Figure 1: Scenario with one submarine and multiple UUVs

1.3 Research Objective

The objective for this research is to lay out the functional and information requirements of a decision support system for the previously described futuristic submarine mission, and then to decide what physical form best supports the functional and information requirements. The proposed decision support system is termed the 'Mission Assistance Tool', also referred to as the MAT. In determining the functional and information requirements of the MAT, several dimensions of the decision support are identified using appropriate analysis techniques. The next phase of the objective is to model a cost-benefit analysis method that could help decide the most suitable display interface for the MAT. This includes examining external factors that drive decision making, as well as costs, benefits, and a tangible way to measure both.

1.4 Research Methodology

Given the research goals and the system design goals, designing the decision support system for submarine mission commanders requires vision and interdisciplinary thinking, as well as the realization of technology boundaries, and human and system limitations. This thesis discusses the need of the customer and the value of the decision support system by doing a detailed cognitive task analysis. From the cognitive task analysis, the functional and informational requirements of the system are generated. Subsequently, these requirements are optimized considering the various possible tradeoffs. The goal is to determine which display interface physical form is capable of fulfilling all the requirements generated in the earlier steps.

However, existing methods for physical form analysis are not sufficient for system acquisition decisions, as they cannot take into account both the subjective and objective functional requirements. Therefore, a new cost-benefit model for physical form analysis is proposed that can be used for analyzing system acquisition or system design decisions, both for futuristic systems and systems where acquisition decisions need to happen early.

1.5 Research Approach

First the functional requirements are identified for the MAT, then the different alternative display forms are introduced which can satisfy the functional requirements. The cost-benefit model is then proposed, which evaluates the different alternative display forms and, lastly a recommendation is proposed.

In generating the information and functional requirements for the conceptual design of the system, a hybrid cognitive task analysis (CTA) is used. The cognitive task analysis (CTA) is an effective analysis technique for deriving design requirements for multi task domains. The traditional CTA approach relies on assumptions and expertise's of subject matter experts, documentation and previous implementations of similar nature. However since the design here is for futuristic missions, no current systems exist from which to draw the assumptions and expertise. Therefore the hybrid CTA framework is used, which allows the generation of information and display requirements for futuristic systems that has no current implementations.

After the CTA, a form must be identified that can satisfy the functions. Traditionally, a cost-benefit analysis (CBA) is done for selecting the functionality and the form is picked without any analysis at all. Traditional cost-benefit analysis considers only monetary terms and cannot take other non-monetary benefits and costs that are associated with decision support systems like the MAT. Therefore, a new methodology is proposed in this thesis for evaluating physical forms, once the functions that the form has to support have been identified. This proposed methodology extends the traditional CBA. Finally, recommendations are made for the display form that best supports the MAT identified functions.

1.6 Structure of Thesis

Chapter 1 outlines the scope, motivation, approach and methodology of this research. Chapter 2 details the Hybrid Cognitive Task Analysis (CTA) performed to generate the functional and information requirements that form the basis for subsequent analysis. In Chapter 3, a new cost-benefit analysis model is proposed. An experimental design, setup and results to support the cost-benefit analysis model is described in Chapter 4. Chapter 5 populates the model with inputs, and discusses results and recommendations. Chapter 6 summarizes the research and provides recommendations for a display interface for the MAT. The chapter ends with identification of possible future work.

2. Cognitive Task Analysis

2.1 Introduction

The first task in this research is generating functional and informational requirements for the 'Mission Assistance Tool' (MAT) through a hybrid cognitive task analysis. In this chapter, the hybrid CTA process is described and the results are discussed.

2.2 Cognitive Task Analysis

Cognitive Task Analysis (CTA) is used to derive interface design requirements and concepts by analyzing a domain [1]. The drawback to the use of CTA is that it relies on predecessor systems and therefore cannot be applied to a futuristic system for which no predecessor exists [2]. To account for this constraint, the hybrid CTA [3] was developed. This hybrid CTA starts with a high-level mission goal or a scenario description of a futuristic system and ends with the information and functional requirements. The hybrid CTA compensates for the lack of subject matter experts and existing system implementations by adopting a multi-tiered approach to requirements generation. This approach consists of the following steps: 1) Generating scenario task overviews, 2) Generating event flow diagrams, 3) Generating situation awareness requirements, and 4) Generating decision ladders for the critical decisions. Finally, from the above four steps, the information and display requirements are extracted. The diagram below depicts the sequence of various stages of hybrid CTA process.

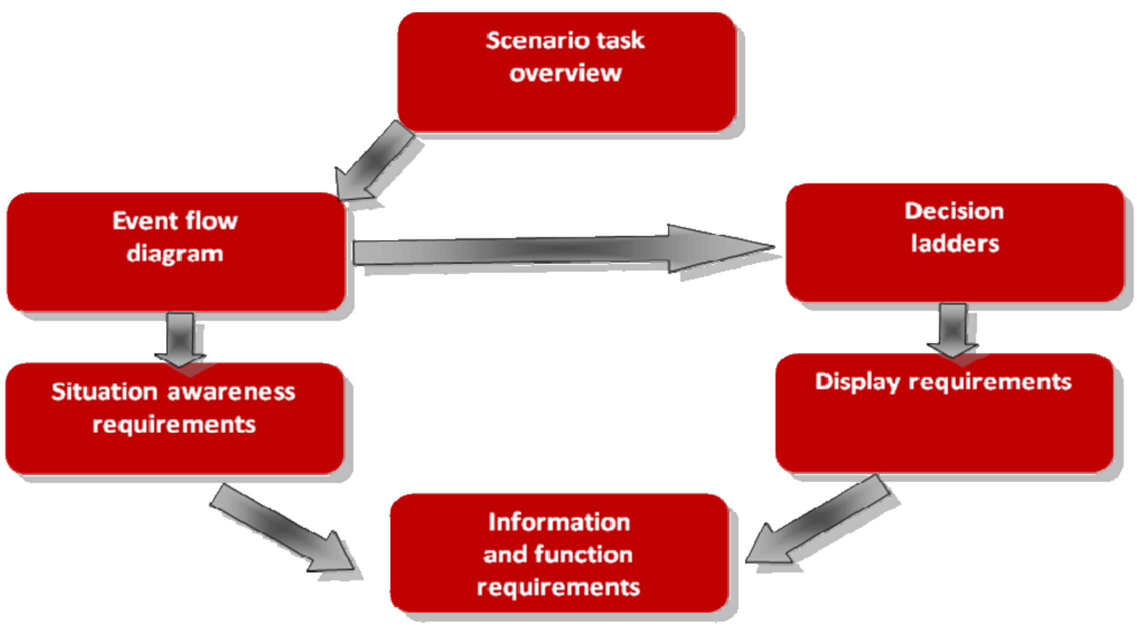


Figure 2: Hybrid Cognitive Task Analysis Process

The following sections details the various steps of the hybrid CTA, including the scenario task overview, event flow diagram, situation awareness requirements, decision ladders, and the resulting information and functional requirements.

2.2.1 Scenario Task Overviews

The hybrid CTA begins with a scenario description of the overall mission. From there, the overall mission is divided into several phases, boundaries of which are identified by the changes in expected operator tasking, both in time and sub-task groupings. For each phase, the sub-goals of that phase are enumerated and the expected subtasks for each of these sub-goals are detailed. Further subdivisions can take place, resulting in a hierarchy, branching from the mission statement, to an individual subtask at the leaf level. The scenario task overview allows for later stage modification or revision of a phase goal or sub-task.

2.2.2 Event Flow Diagrams

Generating an event flow diagram follows the scenario tasks. In this phase, the temporal constraints of the various events in the scenario are detailed. For example, when one particular event must occur in relation to another event, it is outlined in the event flow diagram. Typically, there are three basic categories of events. They are:

- Loops, which represent processes that occur in an iterative fashion with a predetermined condition for stopping further iterations. This predetermined condition could be certain action or starting of another event.
- Decisions, which could be simple decisions (yes/no) or could be the ones that require knowledge-based input from the operator
- Processes that require human-computer interaction to support a mission subtask.

Section 2.5 shows the event flow diagrams for the MAT and explains in detail each of the event flows.

2.2.3 Situation Awareness Requirements

Situational Awareness (SA) is the mental representation and understanding of objects, events, people, system states, interactions, environmental conditions, and other situation-specific factors that could affect human performance in complex and dynamic tasks. It is a critical aspect of time-sensitive command and control operations in human supervisory control. A general definition of SA states that SA as “the perception of the elements in the environment within a volume of time and space, comprehension of their meaning and projection of their status in the near future” [7]. Given this definition, there are three SA levels: perception, comprehension and projection.

Level 1 SA, perception of information, is vital in getting the correct mental picture of the situation. This requires efficient cognitive process and the perception of the needed information. Level 2 SA, comprehension, is the integration of multiple pieces of information and a determination of their relevance to the person's goals. Comprehension also means deriving operationally relevant meaning and significance from the Level 1 SA data. Level 3 SA, projection, is the highest level of SA, where the demand is to forecast the future situation events and dynamics. Operators who have this ability can anticipate future events by projecting from current events. It allows for timely and accurate decision-making.

For the SA requirements phase of the hybrid CTA, SA requirements are generated following the generation of the event flow diagram. The SA requirements are generated under the three different SA levels: Perception, Comprehension and Projection. Each task and subtask of the different mission phases with its constraints identified in the event flow diagrams has its situation awareness requirements. These requirements are categorized under the three SA levels.

2.2.4 Decision Ladders

Decision ladders are used to understand the critical complex decision events of the event flow diagram which need detailed understanding of informational and knowledge requirements to support the decision making process. In other words, decision ladders aid in capturing the states of knowledge and information processing activities necessary to reach a decision [4]. In a decision ladder, human behavior is represented using a three level hierarchy. The first level, the lowest level, is skill-based behavior, generally characterized by volitional sensory motor acts, where performance takes place without conscious control such as what occurs in tracking tasks. At the middle or intermediate level is the rule-based behavior. This level is based on stored rules, which are selected from previous learning in similar circumstances. The third and top-most level is knowledge-based behavior. In this level, behavioral responses of individuals are based on the analysis of cues within the environment and also on the goals of the particular individual [5]. Figure 3 diagrammatically shows the three levels of the hierarchy.

As illustrated in Figure 3, the decision ladder depicts relationships between the levels of causal reasoning (human behavior) and states of knowledge. The figure has two different shapes: boxes and circles. Boxes illustrate the information processing activities involved in each decision phase, and circles represent the information or knowledge produced, which feeds into the next decision phase. In general, after observing the data from the environment, the evaluation and interpretation of the data becomes possible and accordingly, an action takes place.

In the hybrid CTA, the complex decisions embedded in the scenario phases are explained in detail with the help of a decision ladder. A scenario can have multiple complex decisions embedded in it, and each of these decisions is depicted with a decision ladder. A feature of the hybrid CTA process is that each decision ladder has display requirements built into the decision ladders. In generating decision ladders, the various steps are as follows: first, a traditional decision ladder is developed for each critical, complex decision, then two variations of each decision ladder are constructed. In one, the corresponding display requirements are added and in the other, the possible levels of automation are added

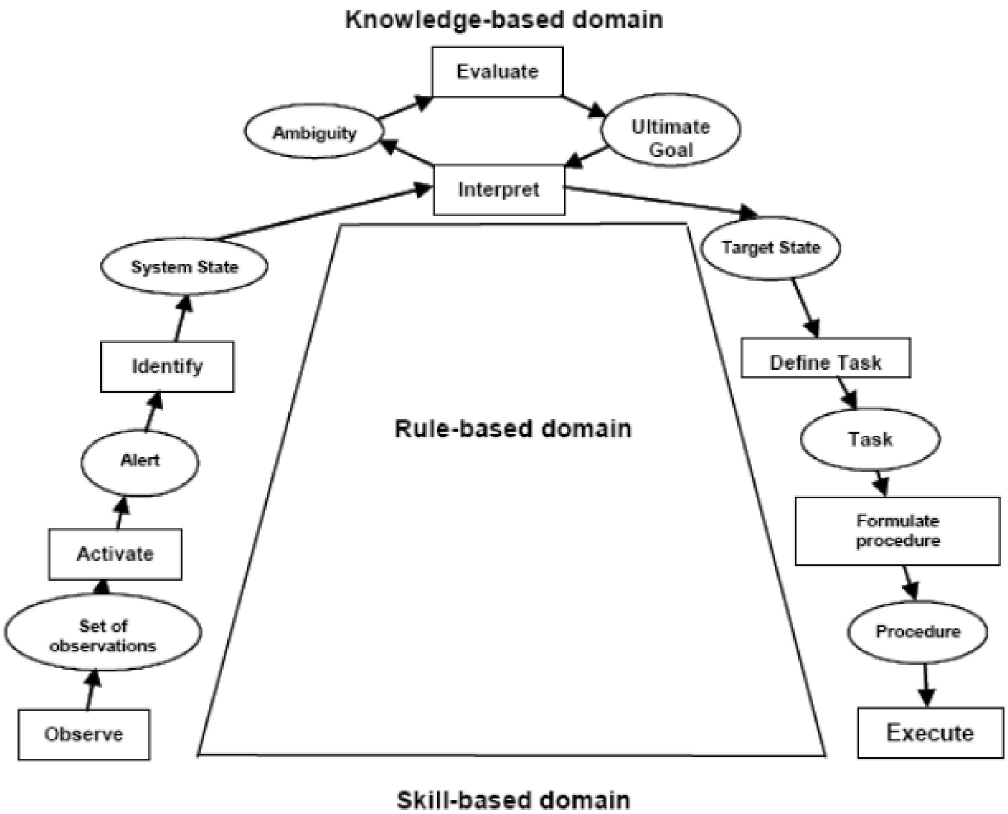


Figure 3: Decision ladder with its hierarchy [6]

2.2.5 Information and Functional Requirements

Information and functional requirements are the final outcome of the Cognitive Task Analysis, which are a direct derivation of the previous steps. Functional requirements specify particular behaviors of a system [7]. A group of information requirements supports each functional requirement. The information requirements define what must be shown on the display to support the user's cognitive process while the functional requirements allow the user to do some action or interact with the external world. The validity of the interface can be verified by tracing the information requirements to the corresponding SA properties and/or the Decision Ladder display requirements that led to the display information requirements.

In the next sections, the hybrid CTA is applied to the submarine scenario defined in Chapter 1.

2.3 Scenario

Operation Active Endeavour [8] is a NATO naval operation that operates in the Mediterranean Sea. It is designed to prevent the movement of terrorists or weapons of mass destruction as well as to enhance the security of the region in general. Submarines are deployed for this mission.

Imagine the futuristic scenario where a submarine is in the Mediterranean Sea in Operation Active Endeavour. The submarine has four UUVs that it can use in the mission. All four UUVs would be launched, operated and recovered from the submarine. Their main purpose would be surveillance and reporting of any unusual activity.

The idea is that the mission commander in the submarine needs a decision support tool for monitoring and controlling the mission (at a high level). The decision support tool is named the MAT (Mission Assistance Tool), which is an independent wireless device that aids the mission commander in gaining situation awareness, and mission planning and re-planning. Since the commander is responsible for ensuring safe and effective operations of all UUVs, along with the submarine, the MAT can aid him/her in the complex, multi-dimensional task.

2.4 Scenario Task Overview

The aim is not only to aid the mission commander in supervising and utilizing the UUVs, but also to aid the commander in monitoring the overall submarine mission. The mission described above is divided into three phases, which are 1) launch of the UUVs, 2) UUV mission execution, and 3) UUV recovery[1]. The MAT is to be used as a guidance tool in maneuvering the submarine to carry out concurrent tasks of effectively managing the four UUVs, while maintaining the safety and integrity of the submarine.

In the launch phase, the UUVs are released from the submarine's torpedo tube. The launch phase is defined as the time the operator commands launch until time the UUV has entered the Mission Execution phase. During this state, the torpedo tube is flooded and equalized, and the UUV exits the torpedo tube. Upon exit, the UUV safely transits to a position clear of the submarine's hydrodynamic influence. The UUV should be safely launched without danger of collision with the submarine or other UUVs at ship speeds (through the water) up to 0.5 knots/3.0 knots in the forward direction, while the submarine maintains a nominal course and depth [9].

In preparation for the launch, the commander can use the MAT to validate the preloaded launch plan of the UUVs given the current environmental constraints and any other new emergent mission requirements. Using the tool, s/he can determine the impact of any last minute changes to the plan including adding, modifying, or deleting predetermined tasks or waypoints of the UUVs.

In the mission execution phase, the UUVs carry out their predetermined plans, including route conformance, surveillance activities, and meeting communication checkpoints. In this phase, it will be critical that the MAT take into account mission limitations such as

[1] It is assumed that detailed mission planning was conducted prior to each launch, and the approved plan has been preloaded into each UUV.

communication latency, and environmental and navigation hazards which could affect a UUV's ability (as well as the submarine's) to adhere to the communication checkpoint schedule. Thus, in this phase, the MAT is effectively the commander's re-planning tool which provides updates for the UUVs including environmental changes, the quality of the mission, alerting tools in case of anomalies, and also some predictive tools to support re-planning in the case of contingency operations.

In the recovery phase, the UUVs are recalled to a rendezvous point at a predetermined time. Recovery is a multi-stage process that includes positioning the submarine's recovery arm, guiding the UUV towards that arm, capturing the UUV, and then directing the UUV to the submarine's torpedo launch tube [10]. Then the data collected by the UUV is offloaded for detailed analysis. Using the MAT, a commander in the submarine can monitor and provide guidance for all these tasks in the recovery phase.

The MAT also will be critical in maintaining submarine safety and collision avoidance during execution of other mission tasks, as health and status monitoring must occur in parallel. It will alert the mission commander when the submarine faces any health and status issues including a major component failure, an on-board system experiencing problems, or a sensor detecting a harmful obstacle. The MAT could display a three dimensional relational picture of the submarine's surroundings and its projected course. If a new ship comes into the submarine's current or predicted operating area, then the MAT will alert the mission commander. In addition, the MAT will have an option to allow the mission commander to check the location data and environmental data of the submarine. These location data parameters could include course/heading, speed, depth, latitude/longitude, time and angle. The atmospheric parameters would consist of air pressure inside the submarine, CO_2 level inside, oxygen level etc.

In short, the MAT will aid in transforming the submarine from an entity that exists in isolation to an entity that controls other remote entities in its ecosystem, thus extending its mission capabilities both in time and in space.

2.4.1 Scenario Task Details

Based on the scenario task overview, the tasks expected from the scenario are listed below. As previously discussed, the different phases are UUV launch, UUV mission execution, UUV recovery, and submarine and UUV health and safety vigilance. While the first three events are time bound, submarine health and safety vigilance happens throughout the course of the submarine's mission. The tasks that the MAT is expected to carry out, categorized under the different phases, are identified in this section.

UUV Launch
Overall Goal: Monitor safe launch of UUVs

- Validate the preloaded launch plan of the UUVs.
- Determine the impact of any changes to the launch and operations plan, if required, and communicate status changes to relevant personnel.

- Portray the nearby environment of the location identified for safe launch of the UUVs.
- Ensure launch location is appropriate with mission plan launch basket.
- In preparation for the UUV launch, ensure that the water pressure in the torpedo tube is suitable for UUV launch.
- Verify the current speed of the submarine to ensure that submarine is at the required speed suitable for UUV launch.
- Check the status of the sea current to understand the impact on UUV launch.
- Monitor the UUVs as they exit from the submarine torpedo tubes.
- Monitor the launch of the UUVs as they each establish themselves on a course clear of the submarine and other UUVs.

UUV Mission Execution

Overall Goal: Supervise UUV mission tasks

- Check if data is available on the MAT from all the UUVs from the last surface point.
- Based on the data available on the MAT, check if any of the UUVs are significantly out of their scheduled resurfacing windows.
- According to the MAT data, determine if all the UUVs have located their potential targets.
- From the data sent by the UUVs when they last surfaced, check that data to figure out if the UUVs have collected information/images of targets, or if one or more UUVs is still in the search loop.
- MAT alerts the mission commander whenever a new set of data is loaded from the UUVs.
- MAT displays all past, present, and future schedule information for all UUVs as well as the submarine.
- Based on the UUV mission data accessible from the MAT, determine if any UUV had any unplanned incident.
- Determine if any of the UUVs missed communication at determined scheduled communication points.
- Display all known and predicted locations of the UUVs (and the submarine) for the entire duration of the scheduled mission.
- MAT alerts the mission commander if any of the UUVs needs emergency recovery.
- MAT generates a recommended course of action if a mission needs to be re-planned.

UUV Recovery

Overall Goal: Ensure secure capture of UUVs

- Validate the preloaded UUV recovery plan, given any changes experienced during the mission execution phase.

- Ensure that recovery location is appropriate with mission plan recovery basket. This could include a re-planning component if one or more UUVs cannot be retrieved in the originally planned basket.
- Verify how many UUVs have entered the recovery stage using the data available in the MAT.
- Display location of the UUVs, especially in relation to the submarine.
- Check the status of the sea and assess the current's impact on UUV recovery.
- Oversee the recovery phase/schedule for each UUV.
- Monitor the UUVs as they are captured by the recovery arm and inserted into the torpedo tubes.
- In case of problems or failures to recover any UUV, MAT alerts the mission commander.
- If recovery mission needs to be aborted or changed, MAT generates a set of recommendations for future course of action.
- In case of an emergency requirement where UUVs have to be recovered urgently, MAT helps to select a new site of recovery, which is clear of any other vessels.
- Once recovery mission is complete, MAT alerts the mission commander.

Submarine and UUV Health & Safety Vigilance
Overall Goal: Submarine health and status monitoring

- MAT alerts the mission commander when the submarine faces any emergency health issue, for example, problems with a reactor or navigation system.
- MAT alerts the mission commander if there is a possible obstacle in the submarine's predicted path. This includes shipping traffic.
- MAT can display a three dimensional relational picture of the submarine's surroundings. At any time, the mission commander has the option to check the MAT for information about the submarine's surroundings.
- MAT gives information about the course of the submarine including the latitude, longitude, and miles traveled by the submarine, as well as predicted path information.
- MAT also provides an option to check the other location data parameters of the submarine. The location data parameters that would be available any time on the MAT screen include course of the submarine, current speed, depth of the submarine, relational coordinate with latitude and longitude, current time, and angle of the submarine's position.
- MAT displays the data about the environmental parameters of the submarine. The atmospheric parameters include information about air pressure inside the submarine, CO_2 level and oxygen level

2.4.2 Assumptions

The following assumptions apply:

- The UUVs are intelligent, surveillance and reconnaissance (ISR) UUVs.

- The submarine is capable of recovering UUVs including the necessary infrastructure such as the recovery arm to capture a UUV and the technology to guide the captured UUV back to the torpedo tube
- The submarine has sensors that can sense any obstacle in the submarine's path.
- There are pressure sensors, carbon, and oxygen level detectors inside the submarine.
- Wireless communications are available throughout the submarine.

2.5 Event Flow

As part of the CTA, after the scenario task overview follows the event flow diagrams. Event Flow diagrams demonstrate the temporal constraints, i.e. the order and relation of the events. Based on the scenario for the mission, four phases take place. They are:

- UUV launch
- UUV mission execution
- UUV recovery mission
- UUV and submarine health/safety vigilance

As discussed previously, the event flow diagram can have three basic event types: 1) a loop that represents a repeated process until some predetermined event occurs, 2) a decision that represents some decision that is required from the commanding officer, and 3) a process which requires some human-computer interaction to support the required task [11]. Each of these event phases is described below with individual event flow diagram examples.

2.5.1 UUV Launch Event Flow Diagram

The entire event flow diagram for a UUV launch is in Appendix A.1. This shows a systematic flow of occurrence of each of the events during the UUV launch. The mission starts with the launch of the UUVs from the submarine. The commanding officer of the entire submarine mission monitors the progress of UUV mission through the Mission Assistance Tool. Looking at the UUV Launch event flow diagram, one can see the analysis of the various possibilities that can occur in each task and subtask of the scenario, where input from the operator is required, and where human-computer interaction takes place to support a task. Apart from the decisions regarding the UUV launch, there is a continual submarine health and safety process, which continues irrespective of the outcome and direction of the launch mission. This is depicted on the right hand side of the event flow diagram in Appendix A.1.

As an example, consider a part of the UUV Launch Event Flow Diagram depicted in Figure 4. This is a subsection of the launch event flow where the UUV launch is not feasible. So the mission commander (i.e., the submarine commanding officer) is faced with the decision of whether to re-plan, postpone, or cancel the mission. He needs relevant information to decide the next move. The MAT generates a list of recommendations based on several existing parameters like UUV launch basket area and payload requirements of the UUVs. These recommendations are based on the new scenario, and whether tasks need to be reassigned to the various UUVs. To aid the decision making for the mission commander, the MAT also generates the next possible steps in case the UUV launch plan needs to be postponed or cancelled.

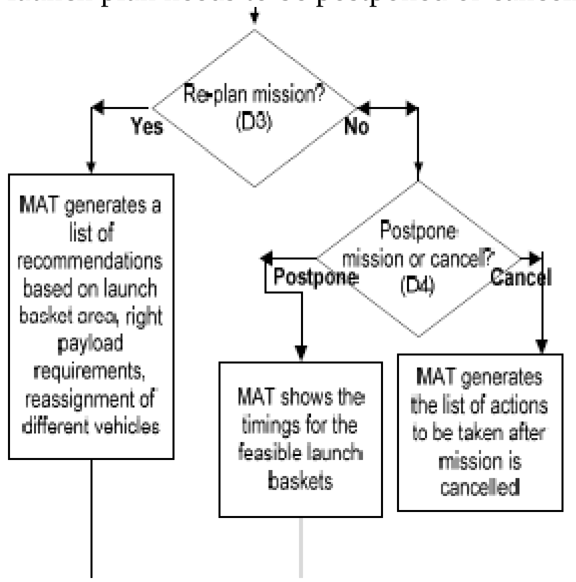


Figure 4: A decision block in UUV launch event flow

2.5.2 UUV Mission Execution Diagram

The mission execution phase starts after the launch of the UUVs. It includes monitoring all the tasks that the UUVs are supposed to carry out, the re-planning or cancelling of mission elements due to off-nominal situations, and the health and status monitoring of UUV and submarine. In the complete diagram (Appendix A.2), there are two blocks on each side, which show an ongoing effort of Submarine and UUV health and safety monitoring.

Figure 5 shows a partial illustration of the mission execution event flow diagram. The event in the diagram is the decision for the mission commander to either accept, reject, or modify the list of recommendations generated by the MAT. This particular decision event arises because of a predecessor decision event where the mission commander decided to re-plan the UUV mission. Once the mission commander decides to re-plan the mission, the MAT generates a list of recommended courses of action that are potential next steps. As can be seen in the partial event flow diagram, the mission commander can accept, reject or modify the recommendations generated by the MAT. If the mission commander accepts the recommendations, then MAT will generate the checklist of items to complete before starting the new mission. If the mission commander rejects the recommendations, then the MAT generates a new plan for the mission. The third option for the mission commander is to partially accept the mission plan recommendations generated by the MAT. In that case, the mission commander can modify some of the recommendation steps and save the modified plan.

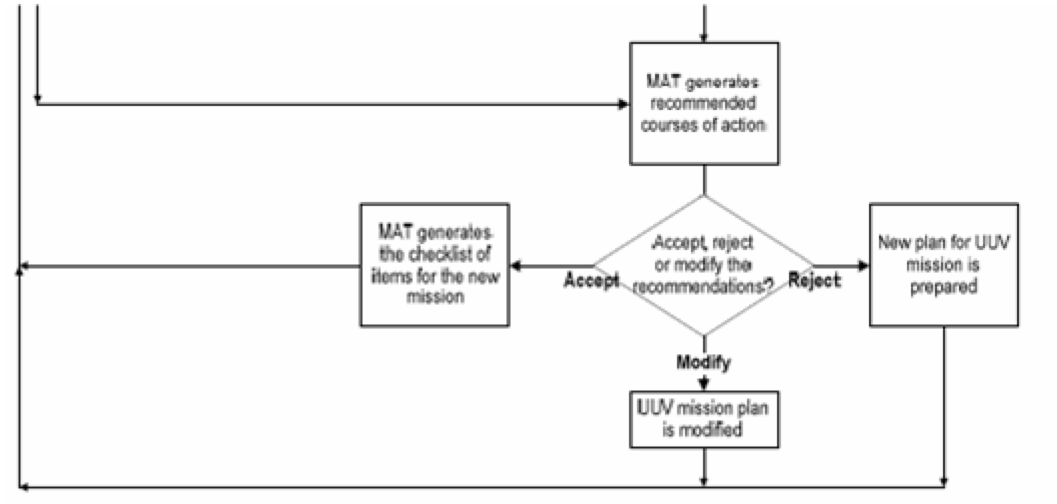


Figure 5: Mission execution (partial illustration)

2.5.3 UUV Mission Recovery

The UUV mission recovery occurs when the UUVs are recovered after a mission is completed, or an off-nominal situation develops which requires one or more UUVs to be recalled. Figure 6 shows the event flow in the recovery phase when the MAT has indicated that a UUV recovery effort is going to start. If the recovery is a planned one, then the MAT will indicate if the original recovery plan is still valid. If it is, then the MAT will generate a checklist of items that need to happen for the safe recovery. If the original recovery plan needs modification under the current circumstances, the MAT will recommend the possible courses of action.

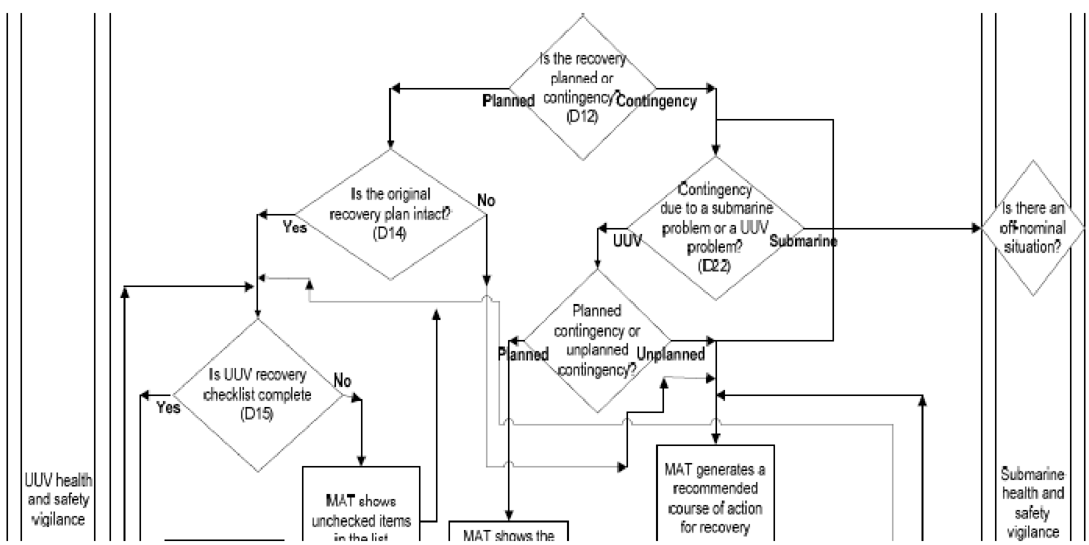


Figure 6: UUV mission recovery (partial illustration)

In case the recovery is a contingency one, the MAT will display the cause of this contingency situation. If the contingency situation is due to a submarine problem, this event flow diagram refers to the next event flow diagram, which is the submarine health and status monitoring. For a contingency situation due to a UUV, the MAT would display whether it is a planned or an unplanned contingency, and then based on this decision, the MAT will generate the next set of actions. The full figure of this event flow diagram is in Appendix A.3.

2.5.4 Submarine/UUV Health and Safety Vigilance

This is a continuous event and takes place anytime the submarine is in operation. Figure 7 shows a partial view of the entire event flow diagram. In this view, there is a decision event, which determines whether the health and safety issue is from the UUV or the submarine. If it is a UUV issue, then the MAT indicates the nature of the issue and its impact on the UUV, as well as the overall impact on the mission. If the issue pertains to a problem within the submarine, then the MAT generates the information about the nature of the problem, the cause of it, and the short and long-term impact of the problem on the overall mission. Appendix A.4 shows the full event flow diagram for the submarine/UUV health and safety vigilance.

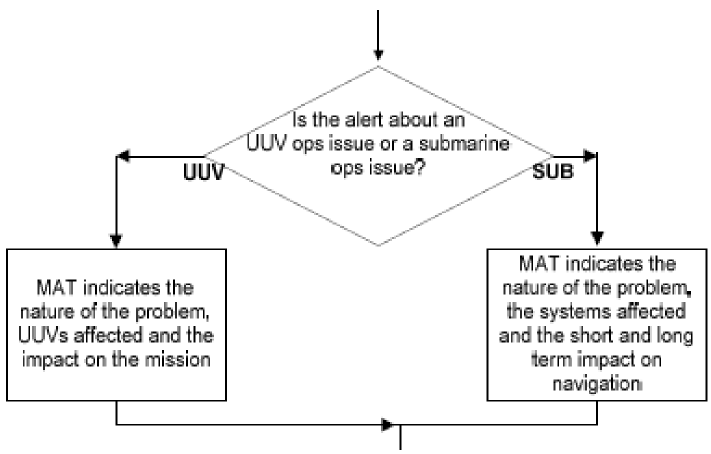


Figure 7: Submarine/UUV health & safety vigilance (partial illustration)

2.6 Situation Awareness (SA) Requirements

Based on the three levels of SA discussed previously (perception, comprehension, projection), a requirements matrix was prepared for all the MAT mission phases, derived from the event flow diagrams. This SA requirement matrix has the mission phase as the heading followed by the requirements in each of the three SA levels. Table 1 shows the complete SA matrix for the Mission Assistance Tool.

Table 1: Situational Awareness (SA) requirements matrix

Event: UUV Launch		
Level I (Perception)	**Level II (Comprehension)**	**Level III (Projection)**
– UUV launch plan – UUV launch basket – Sea current – UUV readiness – UUV operator availability – Submarine readiness to launch – Submarine readiness to communicate after launch	– Launch plan preloaded in the MAT – UUV health status information on the MAT – Information from the UUV launch crews – Checklist of items for UUV launch on the MAT – Information about the surface traffic in the submarine/UUVs' path – Geospatial information relevant for UUV launch – Temporal information that are relevant for the UUV launch	– Possibility to predict UUVs' paths after launch – Information in the MAT about the next available launch basket – Visual indication of UUVs path in geospatial context – How long would it take before the next available launch basket. – Indicate if any UUV could potentially run into health problem during the launch. – Prediction of any task or tasks which may be a bottleneck in the successful UUV launch – Prediction of the navigational difficulties throughout the mission
Event: UUV Mission Execution		
– Location information of all UUVs currently in mission – Activities that the UUVs have completed – Activities that the UUVs are currently doing – Safety and health status of the UUVs – Time left for the mission to end as scheduled – Receipt of new data set for viewing at MAT – An off-nominal situation	– Uncertainties predicted in the mission – Targets/areas that have complete surveillance and the ones that are remaining. – Difference in current verses scheduled plan – Constraints in the way of the pre assigned routes. – Remaining items to be completed – Re-plan the UUV mission	– Possibility to visualize how far the UUVs are in completing their assigned tasks – Problems that might occur within the submarine that impacts the UUV mission
Event: UUV Recovery		
– UUV recovery plan – Recovery site – Contingency UUV recovery – UUVs' current position – UUVs' current health info – Sea current – Submarine readiness to recover UUV – Recovery timeline – Communication with UUV – Navigational problems	– Contingency reason resulting in immediate UUV recovery requirement – Information on the MAT about the latest geospatial location of the UUVs – Constraints in operator work overload for UUV recovery. – Area constraints in the context of the recovery efforts	– Predictions in health & status – Predicted path of the UUVs'. – Predicted traffic in UUV recovery area – Predicted time to capture the UUVs – Collision predictions
Event: Submarine/UUV Health & safety		
1. Off-nominal situation in submarine/UUV health	2. Information in the MAT about the current off-nominal situation regarding submarine/UUV health	3. Visualize the extent of the health alert and the potential impact on the submarine/UUVs 4. Possible courses of action for health issues

2.7 Decision Ladders

In the scenarios of UUV launch, mission execution or UUV recovery, the mission commander is faced with situations where decisions have to be taken. Based on the decision of the mission commander, the course of events can change. Therefore, it is essential to analyze those decisions with decision ladders, so that the decision support tool (MAT) can help the mission commander in those critical situations.

Although, there are multiple decision ladders in this analysis (Appendices B1 and B2), one of them is explained in detail here. The decision ladder for the complex decision of whether to accept the recommendations of the decision support tool (MAT) during an off-nominal situation during UUV launch is explained in detail with Figure 8. This decision ladder starts with an off-nominal situation in the UUV launch event. The box in the bottom-left corner with the title saying 'Activation' is the trigger point of the decision ladder. The left hand side of the ladder consists of situational assessment or analysis and the right hand side consists of response selection or planning.

After the activation, the next stage is the alert phase where the mission commander perceives the alert notification. A set of observations and identification of the present state of the system follows. The word balloons represent display requirements in each of the relevant processing activities or states. For example in the 'Observation' activity, the display requirement in the MAT is to have a checklist of items for UUV launch. The set of observations is followed by an identification of the present state of the system. This is a data processing activity. Every data processing activity, represented by a box, is followed by a state of knowledge resulting from data processing, represented by an oval.

Once the mission commander perceives the information available in the MAT relating to the off-nominal situation, he should have situation awareness of the current state of the mission. The oval named 'System State' in Figure 8 shows that state. Now the mission commander has to evaluate the situation and decide the next course of action, which should be in line with the mission goal. This evaluation phase is represented by the evaluation loop at the top of the decision ladder. This is the knowledge-based domain of the decision ladder. The MAT generates a set of recommendations for re-planning the UUV mission. The mission commander can accept the recommendations, reject the recommendations, or modify the recommendations.

The decision ladder in Figure 8 shows the ambiguity state followed by the evaluation process, and then the interpretation process. The loop between the ambiguity, evaluate, ultimate goal, and interpret activity continues until a desired target state is derived. Once the desired target state is defined, then the suitable task is selected, and the task information is communicated to the relevant parties.

The next state is labeled 'Define Task', meaning it contains the task that will help reach the final goal state. Following that is the 'Formulate Procedure' activity where the various activities that form the whole task are identified. This is the skill-based domain of the decision ladder. Then the next state is the 'Procedure' state followed by the 'Execute' activity. The procedure state outlines the breakdown of several activities that will help to realize the goal state. Then those activities are carried out in the 'Execute' state.

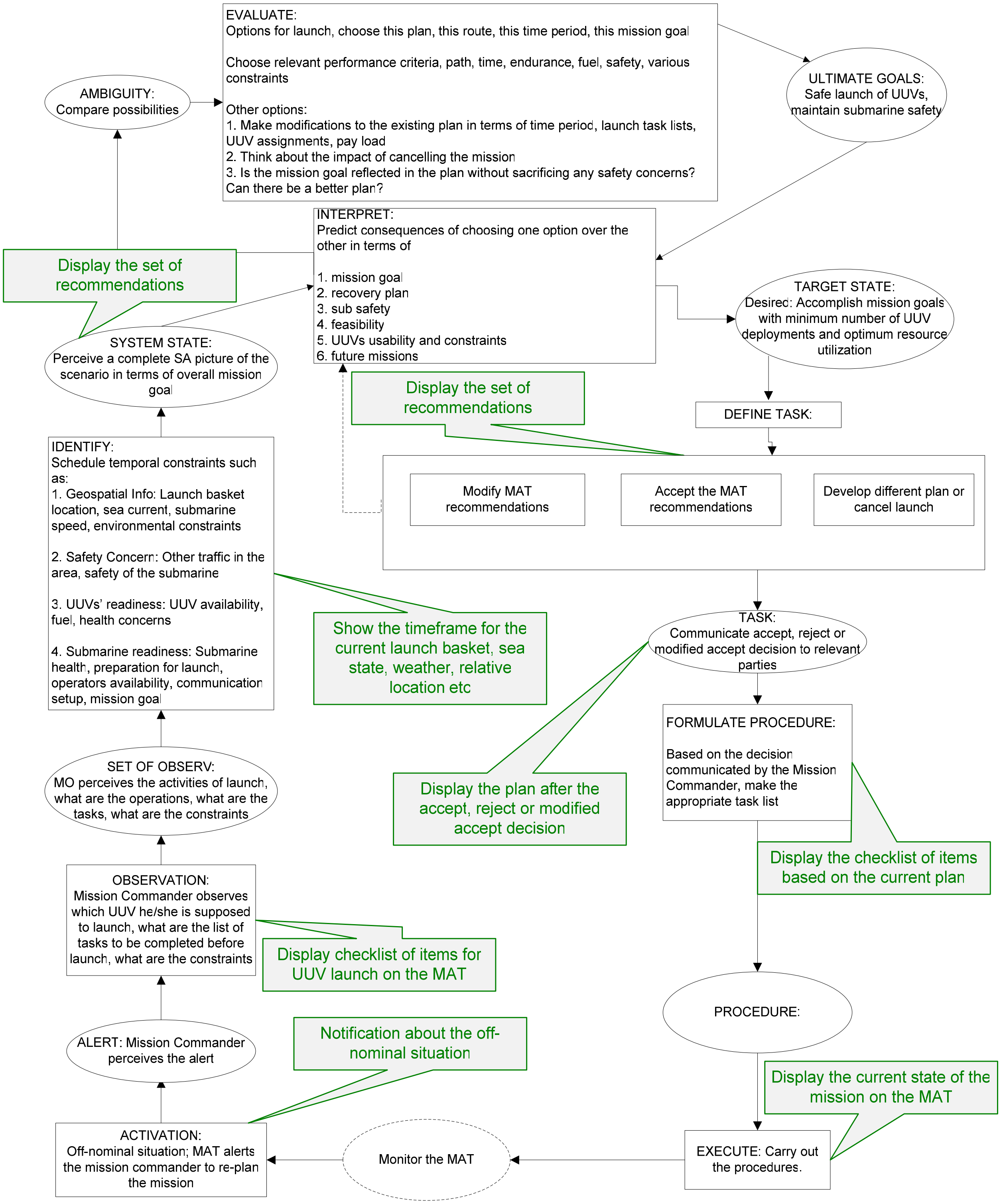


Figure 8: Decision ladder with display requirements for UUV launch

Thus, the decision ladder identifies the key evaluation points and helps define the tasks to reach the final goal. Each of these points needs support from additional information that is fed to the decision ladder as display requirements. Thus, the decision ladder is the significant source of MAT information requirements. Some functional requirements are also understood from the decision ladder. The next section shows the information and functional requirements derived from the decision ladders, as well as from other components of the CTA.

2.8 Information and Functional Requirements

The functional and information requirements are derived from the decision ladders and SA requirements matrix. The three top level functional requirements of the MAT are:

- o Must be mobile
- o Must provide guidance about submarine/UUV mission re-planning
- o Must provide situation awareness and operation guidance for UUVs and submarine

The following tables show the information requirements for the corresponding functional requirements. They are grouped under the functional requirements. The fully expanded functional requirements table is in Appendix C. Table 2 is the list of informational requirements for the functional requirement of providing guidance about submarine/UUV mission re-planning and Table 3 is for the information requirements for providing situation awareness and operations guidance for UUVs and submarine. Each table has three columns, first column states the functional requirement, the second column states the information requirements to support the corresponding functional requirement, and the third column states the source from which the information requirement is derived. 'DL' stands for decision ladder which means that the information requirement was derived from one of the decision ladders while 'SA' stands for situation awareness matrix.

Table 2: Function & Information requirements for submarine/UUV mission re-planning

Functional Requirement	**Information Requirement**	**Source**
UUV mission re-planning	– Display the preloaded mission plan – Visual and audible alert when any off-nominal situation is detected – Display the cause of the off-nominal situation and the approximate place of occurrence – Indicate the severity of the off-nominal situation – Indicate the potential impact of the off-nominal situation on the mission – Indicate the impact of the off-nominal situation on submarine's health and safety – Provide recommendations for recovering from the off-nominal situation – Display recommendations for re-planning the mission – Indicate the impact of cancelling or re-planning the mission – Indicate potential bottlenecks in the mission goals in the context of the off-nominal situation – Display the level of operator workload with and without re-planning the mission	DL DL DL SA DL DL DL SA SA SA

	– Display the alternative pre-plans for UUV mission. – Indicate the recovery impact of re-planning the mission – Indicate the schedule verses geospatial impact of re-planning	SA SA
Submarine mission re-planning	– Display the submarine mission plan – Visual and audible alert when any anomalous condition is detected – Display the type of anomaly, whether it is geospatial, system or schedule anomaly – Display the cause of the anomaly – Indicate the severity of the anomaly and its potential impact on the mission – Indicate the impact of the anomaly situation on submarines' health and safety – Indicate the impact on the UUV mission – Provide recommendations for recovering from the situation – Display recommendations for re-planning the mission – Indicate the impact of cancelling or re-planning the mission – Indicate the navigation impact of re-planning – Indicate the impact of re-planning on recovery of UUVs	DL DL DL DL SA DL DL DL DL DL SA SA

Table 3: Functional and information requirements for providing situation awareness and operational decision support

Func Reqr.	Information Requirement	Source
Guidance about health and safety of submarine	– Display the reading of all the sensors onboard the submarine – Indicate the sensor readings for perishable items like fuel, oxygen level, etc. – Visual and audible alert for any sensor reading which is below threshold label – Indicate causes of the alerts – Indicate the impact of the alert on the overall mission – Display recommendations to fix the problems that caused the alert – Visual alert for any perceived external threat to the submarine – Show the predictions for the overall health of the submarine – Display trends for the temporal variables.	DL DL DL DL DL SA SA
Guidance about health and safety of UUVs	– Display the sensor readings of all the ones attached to the UUVs. – Visual and aural alert for any sensor reading below warning label – Indicate causes of the alerts – Indicate the impact of the situation on the overall mission – Display the recommendations in response to the alert (cancel/abort mission) – Visual alert for any perceived threat to the UUV that is external to the UUVs – Visual alert for any system failure in the submarine that could impact UUVs – Visual and aural alert if any UUV's health status cannot be reported – Visual and aural alert if any UUV has failed that prevents its recovery – Indicate potential uncertainties in the UUV track	DL DL DL DL DL SA SA DL DL SA
Geospatial information of submarine & operating UUVs	– Display relational map of the submarine/UUV and its geo-spatial surroundings – Display submarine's location parameters like current speed, depth of the submarine, relational coordinate with longitude and latitude and angle of submarine's position – Display the location parameters of the UUVs for recovery – Display the expected path of the submarine/UUV – Display the launch basket location of the UUVs	SA SA & DL DL SA

	– Display all UUVs' current position – Display the UUVs' expected paths – Display in a geo-spatial map all the UUVs in operation along with the submarine and any other traffic – Display the possible recovery areas for UUVs and the selected ones. – Display the area of operation of the UUVs	DL DL SA DL SA DL
Temporal progress updates	– Display checklists of tasks assigned to each UUV and tasks successfully completed, tasks that failed to complete and tasks that are still to be attempted. – Display time remaining for the mission to end. – Display modifications in UUVs original route – Display comparison of original vs. current vs. predicted route of all UUVs – Indicate the number of tasks for each UUV – Indicate time to completion for each UUV's current tasks – Visual and aural alert when any UUV fails to communicate as scheduled – Visual and aural alert for any off-nominal situation of UUVs – Visual alert when any UUV detects its target – Visual and aural alert if UUV communication indicates that it has gone into an unscheduled area – Visual and aural alert when any UUV has not communicated as scheduled – Indicate the elapsed time since when the UUV(s) have been lost or stopped functioning – Display the time for the next communication point of the UUVs – Display the time window for next recovery window of the UUV – Display the time window for the next UUV launch basket	DL DL SA SA DL SA DL DL DL DL DL DL DL DL DL

2.9 Summary

The hybrid CTA provides the functionalities and information requirements that the Mission Assistance Tool must support. Now that the functional and associated information requirements are known, before the actual software can be designed to support the requirements, the device's physical form must be known, i.e., given all the different kinds of mobile technology available (e.g., tablet PCs, handheld devices, etc.), which will best support the requirements? It is important that this physical form be identified as early as possible in the system acquisition process so that any other additional system requirements are identified. For example, the physical form of the MAT could add additional requirements for a certain type of wireless network throughout the submarine, which need to be taken into account as early as possible.

Thus, the next phase of this research is to conduct a cost-benefit analysis that compares candidate mobile display technologies to determine the physical form of the MAT decision support tool. This is not a trivial process as there are many human-system concerns that need to be taken into account to determine the best physical form, i.e., usability (both objective and subjective), weight, etc. However, this is very difficult to do in the conceptual design phase without developing working prototypes of each of the candidate devices, which generally is cost and time prohibitive. The focus of the next two chapters is developing a methodology that allows for objective display comparison early in the acquisition process. The goal is to determine, given the known functional and information requirements, which display physical form will support the functional and information requirements but also take into account other important variables such as cost and usability.

3. Proposed Cost-benefit Analysis Model

3.1 Introduction

In order to determine the most optimal physical form of display for the MAT, a utilities based cost-benefit model is proposed. The calculation of utilities revolves around the various '-ilities' expected from the system. Selection and quantification of the '-ilities', the extraction of utilities, and the application of utilities for cost-benefit analysis forms the basis of this chapter.

The job of a systems engineer often involves trading cost (broadly defined as acquisition, development, and life cycle), benefit, and development schedule. Conventionally, one of the parameters can be set to a prescribed value, one optimized, and the other left free to vary. Thus, it is important to ensure that all key decision makers know which variables to assign to which category. The primary link between benefit and cost is system architecture, where is defined by the functional requirements (Chapter 2) and the resulting physical form. This chapter proposes a cost-benefit model that can be used to choose among available physical form options in any human-systems integration effort.

3.2 Cost-Benefit Methodology

Cost-benefit methodologies involve cost-benefit analysis across multiple options. Usually, multiple parameters define each option, and traditional cost-benefit analysis across all parameters may not be feasible. This is because each parameter has a different basis for comparison and traditional cost-benefit analysis may not be adequate for such comparisons [12]. Therefore, the proposed model is a utility-based cost-benefit analysis of the various system '-ilities'. The following paragraphs give formal definitions of the various components of the model including cost-benefit analysis, utility, and '-ility'. Subsequent sections discuss the proposed model.

3.2.1 Cost-Benefit Analysis

Cost-benefit analysis supports better decision making early in any project. The process involves weighing the total expected costs against the total expected benefits of one or more options in order to choose the most profitable option. Traditionally all costs and benefits are expressed in terms of monetary value. Since many of the costs and benefits are realized in the future, the present value or worth of the benefits and costs needs to be determined [12]. One challenge is in non-monetary benefits and costs. Utility, an alternative measure for cost-benefit analysis, can be used for both monetary and non-monetary costs and benefits. In other words, utility can measure both subjective and objective cost and benefit.

3.2.2 Utilities

Utility is a measure of relative happiness or satisfaction gained [13]. The utility of a alternative is the quantification of a person's relative preference for that option. A utility function can be used to express a person's relative preferences among a set of consequences. Utility is a useful measure in cost-benefit analysis because apart from expressing benefits in monetary terms, it quantifies benefits.

3.2.3 '-ility'

An '-ility' is the characteristic of a system that is an aspect or a non-functional requirement of the system [14]. They are so named because the majority of those non-functional requirements end in '-ility'. Some of the common '-ilities' are manageability, maintainability, serviceability and reliability. A few of the '-ilities' that are relevant for the MAT are affordability, portability and usability Usually, an '-ility' applies across a set of functional requirements. For example, reliability applies across multiple functional or system requirements. Usability, which is another 'ility', is also associated with multiple functionalities of any product including user interface for products with human computer interaction.

3.3 Proposed cost-benefit analysis methodology

The proposed methodology for cost-benefit analysis brings together costs and benefits, some of which may or may not be measurable in monetary terms. The result of applying this approach is an overall utility value for each display form option of the MAT. This utility value takes care of both subjective and objective benefits and uses sensitivity analysis to understand the variability in cost and benefit parameters. Thus, the complexity of the decision maker's job is reduced, as the option with the highest overall utility can be recommended as the best available option.

The 8-step-process for the proposed methodology is:

1. Select the various '-ilities' to be addressed
2. Determine the attributes of each '-ility'
3. Calculate the respective weight of each attribute
4. For each '-ility', quantify attribute values for each available option. This could be monetary value, operational performance or another appropriate value. Since this model focuses on determining the best physical form, an appropriate human factors calculation is used.
5. Calculate the utility value of each attribute in that '-ility'
6. Calculate the additive utility (utility * weight) for each attribute
7. Repeat step 4 – 6 for each '-ility' identified in step 1
8. Choose the option with the highest overall utility value.

This '8-step process' is used to decide which physical form is most suitable for the MAT, and is discussed in the following sections.

3.4 Selection of '-ilities' and attributes

The first step of the proposed methodology is to determine which '-ilities' are particularly relevant for the system under consideration, which in this case is the display interface of the MAT. First, an exhaustive list of '-ilities' is prepared. It is pruned to include only those ilities that are deemed to affect the system most. Along with identifying the '-ilities' list, the factors that affect the particular '-ilities' also have to be identified. These factors will likely be different for different systems.

Based on the functional and informational requirements of the MAT display, the ilities that are most relevant along with their associated factors are as follows:

1. **Affordability –** This is a detailed examination of an institute's or individual's ability to afford a particular system, taking into consideration the costs, benefits, and liabilities. In this case, the costs and benefits are in monetary terms. Attributes relevant to affordability for the display interface of MAT are:
    a. Acquisition costs/Overhead savings
    b. Development costs/Productivity increase
    c. Operations costs/Maintenance savings
2. **Dependability –** The trustworthiness of a system to deliver service that can justifiably be trusted [15]. Factors relevant to dependability of the MAT display interface are
    a. Availability: Readiness for correct and desirable service
    b. Reliability: Continuity of available service
    c. Safety: Absence of catastrophic consequences on the user(s) and the entire system
    d. Security: Concurrent existence of authorization, confidentiality, and integrity
3. **Maintainability** - A characteristic of design and installation, expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources [16]. The factors in maintainability that are most relevant for MAT are:
    a. Maintenance costs/benefits
4. **Portability –** The ability of being easily transportable from one location to another. The factors which affect portability in the context of MAT are:
    a. Weight
    b. Volume
5. **Flexibility –** In engineering system terms, flexibility is the ease with which a system can respond to uncertainty, and still sustain or even increase the value delivered. The factors that are to be considered in flexibility of the MAT display interface are:
    a. Ease of implementing changes to current functionalities or adding new ones.
6. **Usability –** Usability is a measure of how effectively a user can interact with a product or system [17]. In other words, it is the classification of how easy it is to

learn or use the product or system. For the display interface of the MAT, the following factor(s) are considered as a measure of usability:

a. Movement time in performing a task
b. Amount of difficulty experienced in the task
c. Measure of performance

3.5 Calculating the weight of each attribute

The relative weights for each attribute, are calculated by the Analytical Hierarchy Process (AHP) process [18]. AHP is a technique for decision making when there are a limited number of choices and each choice has a number of attributes associated, some of which may not be easy to formalize [19]. AHP can be used to weigh selection criteria and analyze the data collected for those criteria. Using AHP, comparative judgment is made by pair wise comparison of the elements within a given level. Equation 1 shows the AHP matrix. The entries in that matrix reflect the priorities of elements in that level. Based on this approach, the pair wise comparison between a pair (p, q) of elements is dependent on the question of how important element p is over element q. The responses are designated by a_{pq} in a comparison matrix of order n x m, $[A]_{n \times m}$. The form of the matrix for n,m = 3 would look like this

$$[A]_{3x3} = \begin{bmatrix} 1.0 & a_{12} & a_{13} \\ a_{21} & 1.0 & a_{23} \\ a_{31} & a_{32} & 1.0 \end{bmatrix}$$

Equation 1: AHP Matrix

For the model proposed here, any entry in the matrix can take the integer values of 1-5. Therefore, comparison of the two attributes can take any of the following values.

Equally important	1
Moderately important	2
Strongly important	3
Very strongly important	4
Extremely important	5

For example, if the comparison is between the attributes 1) weight and 2) volume, and weight is strongly important over volume, then $a_{12} = 3$. Using this matrix, the weight for each attribute is determined by calculating the normalized principal eigenvector $[W]_{nx1}$. Chapter 5 shows an example of using the AHP matrix for finding the specific weights of MAT individual attributes.

3.6 Calculating the Utility for each '-ility'

The utility calculation procedure for each individual '-ility' could be unique. For example, in the affordability case, the most appropriate form of utility can be derived from the cost-benefit analysis of its various factors. On the other hand, for dependability, the most appropriate form of utility can be derived from expert opinion about the various factors. For usability, as will be demonstrated, Fitts' law, a general model for human-computer input interaction, is used to calculate the usability utility of a display in terms of data input. Thus, the utility can represent cost, subjective assessment, or objective assessment using standardized models.

There are often conflicting objectives between the various factors within a particular utility. For example, in portability reducing weight but increasing volume may conflict. A relatively straightforward way of dealing with conflicting objectives is the additive preference model, which is the calculation of a utility score for each objective and then adding the scores, weighting them appropriately according to the relative importance of the various objectives [20]. The additive preference model is represented by an additive utility function [20]. The additive utility function is used in this proposed model, which is discussed further in the next section.

3.6.1 Additive Utility Function

The additive utility function has two kinds of elements: 1) the scores of individual attribute scales, and 2) the weights of the corresponding attributes. It compares the different attributes in terms of their importance, and is the summation of the individual utility functions multiplied by their individual weights. So, for the individual utility functions $U_1(x_1)$, $U_2(x_2)$,…$U_m(x_m)$ for m different attributes x_1 through x_m, with individual weights of k_1,….k_m, the additive utility function would be

$$U(x_1, x_2, \ldots x_m) = k_1 U_1(x_1) + \ldots + k_m U_m(x_m)$$

$$= \sum_{i=1}^{m} k_i U_i(x_i)$$

All the individual weights, k_1 through k_m, are positive and should add to 1. The additive utility function also assigns the values of 0 and 1 to the worst and best conceivable outcomes respectively.

For the purpose of this analysis, the first (affordability) and the last (utility) '-ility' in the list are considered. Therefore, the proposed method is applied to find the utility values of affordability and usability. These two are chosen because they are two distinct '-ilities' and require entirely different approaches to calculate their individual utilities. The inclusion of the remaining ilities in the model is an area for future research.

3.6.2 Applying '8-step-process' to 'Affordability' and 'Usability'

The following chapter demonstrates the application of the '8-step-process' to the '-ilities' of affordability and usability. These two '-ilities' are quite different from one another, as affordability can be measured in monetary terms while measure of usability cannot be measured in monetary terms. Because usability also has both subjective and objective measures (preferences vs. performance measures), some other metric is needed to objectively compare different MAT physical form options. The focus of the next chapter is the development of this metric, which allows for objective usability comparisons for the possible MAT physical forms.

3.7 Summary

The proposed methodology has broad implications for the human-systems integration aspect of the system engineering process. System acquisition decisions must generally be made early in the process, i.e., before a submarine can be built to support multiple UUV operations, thus it is critical that necessary support for subsystems be identified as early as possible. This proposed cost-benefit analysis model supports the conceptual phase of the system engineering process by combining monetary and non-monetary costs, and subjective and objective benefits, to give acquisition decision makers a coherent picture. By presenting a utility value of each available option expressed in numerical terms, the decision makers can judge the overall utility of each option by the final utility value.

Chapter 4 details the development of a usability metric that allows for physical form comparison. Chapter 5 integrates the objective and subjective values of usability and the affordability to determine the overall ranking of MAT physical form options.

4. Determining the Utility of Usability

4.1 Introduction

To calculate the utility for usability of the various forms of display devices, an experiment was conducted to determine the performance of each display device in order to generate an objective usability metric. As will be discussed in detail, Fitts' Informational theory [21] is used to determine task performance.

Fitts' law is a relation derived from information theory [22] which models human movement. Fitts' law models rapid, aimed, movements, where one appendage (like a hand) starts at rest at a specific start position, and moves to rest within a target area. Fits' law is given by:

$$MT = ID / IP$$

where MT is the Movement Time, the time required to complete the motion, ID is the index of difficulty of the task (defined below), and IP is the index of performance. The index of performance is a constant for a specific appendage. Movement time is commonly measured in milliseconds, the index of difficulty in bits, and the index of performance in bits per second.

The index of difficulty was originally defined by Fitts [21] as:

$$ID = \log_2(2 A / W)$$

Where A is the amplitude of the movement (the distance from the start position to the centre of the target); and W is the width of the target. Both A and W are measured in units of distance (millimeters).

Currently, the preferred formulation is that proposed by MacKenzie [23]

$$ID = \log_2 (A / W + 1).$$

This is the preferred formulation because it always yields a positive index of difficulty and provides a slightly better fit with empirical data than the other formulations [24].

In this research, Fitts' law is used for calculating usability for several physical forms of displays. Usability is more often associated with subjective preference. However, Fitts' law can capture objective usability and quantify it. As shown above, measures such as index of performance, index of difficulty, and movement time captures parameters that predict user performance under different human psychomotor conditions. As will be shown, this can be an effective measure of comparative usability.

To calculate usability to be represented in the cost-benefit model, an experiment was designed. It involved a map-pointing task that is a core part of the functional requirements of MAT, which addresses the speed-accuracy trade-off. User performance was measured while carrying out the task across different display forms. Fitts' law was used to calculate the different usability parameters of movement time, index of difficulty and index of performance.

4.2 Hypotheses

To establish the attributes for usability, it is important to determine which attributes significantly impact usability. These hypotheses below will prove which among the following attributes of usability should be considered for the cost benefit model. The attributes in consideration are index of difficulty, index of performance and movement time.

- H1: Size of display (size in the field of view) is directly proportional to the index of performance for a user task
- H2: Size of display (size in the field of view) determines the index of difficulty for a user task
- H3 Movement time is dependent on device and input type

The hypotheses are not ranked in the order of their importance. All the three hypotheses are tested in the experiment.

4.3 Display forms and software

Based on the functionality generated in Chapter 2, the display form of MAT has to be mobile and portable with wireless capability. The form factor is a critical issue and the experiment will help to determine which form factor gives the best usability performance. Taking into consideration the requirements of the physical form, three display forms were selected for the experiment. These three forms satisfy the conditions laid out in the functional requirements. Evaluation of these three forms using the experiment and the cost-benefit model will determine the best option. The three physical display forms are:

- Video wear display
- Handheld device (micro PC)
- Tablet PC

ICuiti manufactures the video wear, the micro PC is manufactured by Sony and the tablet PC is manufactured by Fujitsu. Figure 9 a, b, and c shows the various forms of display.

Two different input types, mouse and touch screen, were used with the different display forms. These two input types were selected because they are the most relevant input types based on the functional requirements of the MAT. The combination of the display form and the input type used in the experiment was as follows:

i) Standard tablet PC (Fujitsu T Series Lifebook) with mouse input
ii) Standard tablet PC (Fujitsu T Series Lifebook) with touch screen input
iii) Micro PC (Sony Vaio UX Series) with mouse input

iv) Micro PC (Sony Vaio UX Series) with touch screen input

v) Head-up eyeglass display, the ICuiti video wear display, connected to the standard tablet PC with mouse input

Figure 9: a) ICuiti video eyewear, b) Sony Vaio micro PC, c) Fujitsu Lifebook tablet PC

4.4 Experiment

In real life, the tasks that are expected of the MAT are complicated. One such task is map pointing and target capture. The purpose of this experiment was to calculate the objective usability of the different display forms.

Target capture in this experiment required locating target cities in the map of USA and clicking on the correct city to designate it as captured. The input device was either a mouse or a stylus. The subjects moved the input device and tried to capture the target as quickly and accurately as possible.

4.4.1 Experimental Setup

In this experiment, the subjects acquired targets on a map. Targets were presented one at a time. The map used here was the political map of USA and the targets presented were the various cities and towns within the USA. The order in which target city names appeared was preselected before the experiment began. The subjects had no prior knowledge of the name of the cities or the order in which they would appear. In some states, similar city names made the identification of cities more difficult and increased the chance of errors committed by the subject. The distance moved by the subject, (amplitude) was captured, along with the width of the target (the final width of the state in mm as it appeared after the subject had zoomed in on it as shown in Figure 10b) and the movement time. From this data captured, the index of difficulty, the error index and the index of performance were calculated

4.4.2 Subjects

The subjects of this experiment were six graduate and undergraduate students (3 of each). All the subjects were experienced computer users. Each subject participated in all experimental scenarios.

4.4.3 Apparatus

The map pointing software [25] was loaded onto a tablet PC and a micro PC. The displays were the screens of the tablet PC, the micro PC and the ICuiti video wear display that was connected to the tablet PC. The input devices were mouse and stylus (touch pointing) for tablet PC and micro PC, and only the mouse for video wear. The screen resolutions used for the tablet PC and micro PC were 1280 x 1024 pixels, and for the video wear it was 640 x 480 pixels.

4.4.4 Procedure

Subjects performed multiple runs of this experiment using the three different display devices. The operation of the devices and requirements of the tasks were explained and demonstrated to each subject before beginning. Each subject carried out two warm-up block of trials prior to data collection.

The tasks in this experiment were target state selection and target city capture. The forms of input software were mouse or stylus. The subjects captured the target by pressing and releasing the mouse button or applying and releasing pressure on the stylus and then clicking the button labeled capture. An arrow appeared in the center of the map, which was to be dragged to the target state (Figure 10a). Then the width of the state was zoomed in in order to find and capture the target city (Figure 10b). After each successful capture, the arrow moved back to the center of the map and the map was reset. Each set had ten target cities to be captured and each subject had to carry out two sets of the experiment on each device.

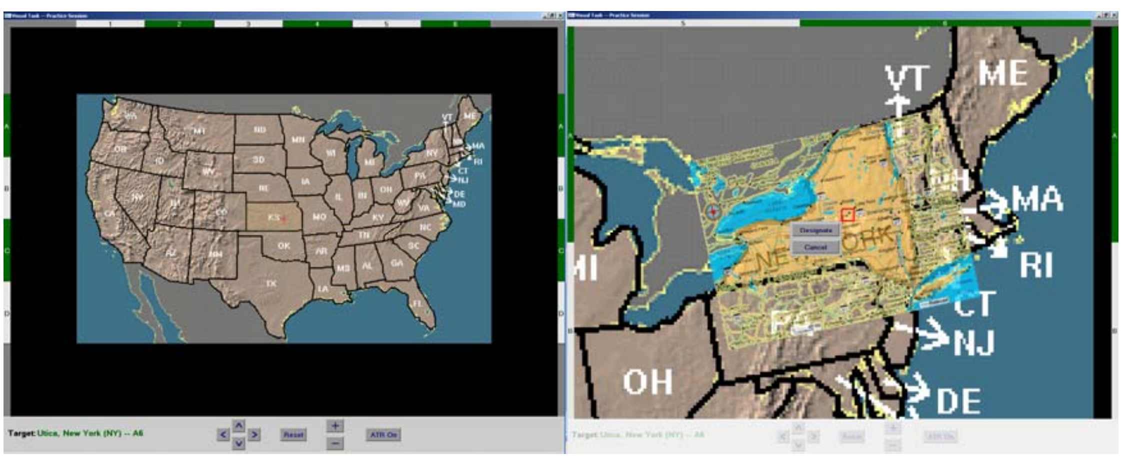


Figure 10: a) First screen of the map pointing experiment. The target city to be captured appears at the bottom of the screen.   b) The screen after the subject has zoomed in on the state and locates the target city. The subject captures the target city by clicking the Designate button.

4.4.5 Design

The controlled variables were device (three) and task (one). Dependent variables were amplitude (A), width (W), movement time (MT), index of difficulty (ID) and index of performance (IP = MT/ID). There were three matrices, one for each device form. The three devices were micro PC, tablet PC and ICuiti video wear. The sole task was target capture on a map. The amplitude (A) was the distance the subject moves the cursor to reach the target city. The width (W) was the width of the zoomed in state, similar to the one seen in Figure 10b. The width varied depending on how much the subject zoomed in. Movement time was measured from the beginning of a move to search a city to the button-down action to point to the right city.

The experiment was conducted on a single day for all the three devices in random order. Each subject completed his/her experiment for all device/task combinations in a single sitting.

4.4.6 Results Capture

The results from this experiment were captured in text files in a specific format. A typical file format of this experiment is shown in Appendix D. The results are analyzed in the analysis section.

4.5 Analysis

The goal of this experiment was to compare the performance of several device-task combinations using Fitts' information processing model. This data analysis is subsequently used in the cost-benefit analysis. Appendix E shows a sample data file generated from the experiment. Table 4 shows the results of experiment. There is no touch pointing input for the video wear.

Table 4: Summary of the Movement Time, ID and IP from the experiment

	Movement Time		ID		IP	
Device	Mouse	Touch Pointing	Mouse	Touch Pointing	Mouse	Touch Pointing
Tablet PC	20.74	20.98	1.47	1.88	0.089	0.102
Micro PC	23.36	14.34	1.54	1.95	0.085	0.138
Video Wear	32.05		1.75		0.074	

4.5.1 Movement Time

Across the device-task factors, the mean value of movement time for the tablet PC, micro PC and video wear were 20.7, 23.35 and 32.05 seconds for mouse input and 20.9 and 14.3 seconds for touch input. Figure 11 shows the comparison in a graph

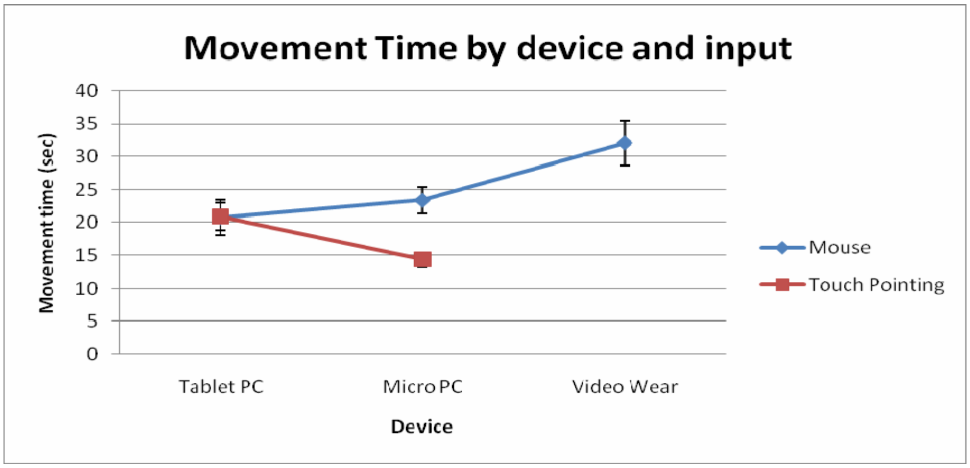


Figure 11: Comparison of movement time (MT) among devices

The standard errors represented by the black line on the nodes of tablet PC and micro PC overlap, however there is no overlap for the video wear. While the movement time increases from tablet PC to micro PC to video wear for a mouse input, the movement time decreases from tablet PC to micro PC for touch input. Thus, the hypothesis that movement time is dependent on device and input type (**H3**) may not always be true.

4.5.2 Index of Difficulty

Across the device-task factors, the mean value of index of difficulty for the tablet PC, micro PC and video wear were 1.46, 1.53 and 1.75 bits for mouse input and 1.88 and 1.95 bits for touch input. Figure 12 shows the comparison in a graph

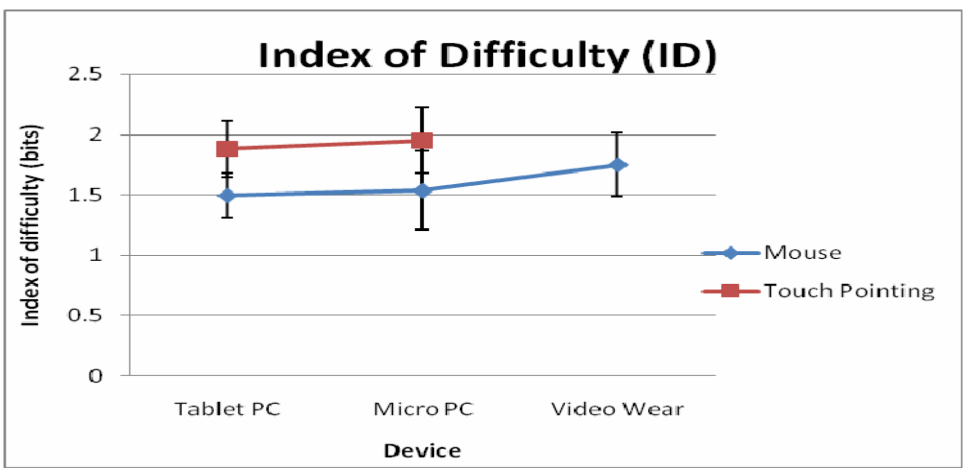


Figure 12: Comparison of index of difficulty (ID) among devices

From this graph, it can be seen that index of difficulty (ID) increases from tablet PC to Micro PC to video wear for both types of input. The standard errors represented by black overlap for all the devices. Thus the hypothesis that size of display determines the index of difficulty for a user task (**H2**) is rejected.

4.5.3 Index of Performance

Across the device-task factors, the mean value of index of performance for the tablet PC, micro PC and video wear were 0.089, 0.085 and 0.073 bits for mouse input and 0.102 and 0.138 bits for touch input. Figure 13 shows the comparison in graphical form

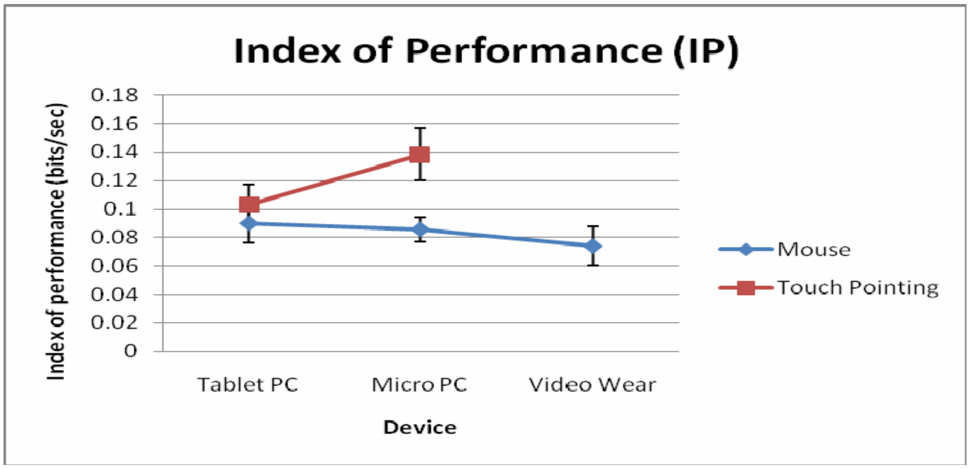


Figure 13: Comparison of index of performance (IP) among devices

From this graph, it can be seen that index of difficulty (IP) decreases from tablet PC to micro PC to video wear for mouse input but increases from tablet PC to micro PC for touch pointing input. The standard errors represented by black solid lines in the nodes do not overlap.

Therefore, the hypothesis that size of surface area of display is directly proportional to the index of performance for a user task (**H1**) holds true tentatively although type of input is a big factor for the determination.

From the three hypotheses, H2 is rejected for the options in consideration, so the attributes for consideration in the cost benefit analysis of usability are movement time (MT) and index of performance (IP).

4.6 Summary

The experiment has provided a basis of comparison for the three display devices. The results obtained give an objective way to compare the user performance when the size in the field of view is different. A bigger the field of view does not always mean better user performance. However the form of input also plays a big role, as can be seen from the comparison of IP.

These results form the basis of comparison for the cost-benefit model. They also determine that the attributes to consider for measuring the utility of usability are movement time (MT) and index of performance (IP).

5. Cost-Benefit Analysis: Calculating Utilities

5.1 Introduction

Cost-Benefit Analysis is a methodology that can help appraise, or assess project or proposal aspects, and thus help make decisions. The process involves weighing the total expected costs against the total expected benefits of one or more actions or processes, and then choosing the most profitable one. Therefore, in general, cost-benefit analysis is an economic tool to help in decision-making. Its practice is prominent in both government and the private sectors.

Cost-benefit analysis determines the value of an intervention in relation to the status quo, and is computed in terms of willingness to pay for the benefits versus willingness to pay to avoid the costs. All the stakeholders affected by the intervention are listed and a monetary value is placed for the benefit that each stakeholder will derive from the intervention. Costs are the monetary value of the initial and ongoing expenses. Monetary values can be assigned to tangible elements as well as those less tangible, such as loss of reputation or effect of total project failure. However, there are certain elements such as personal preference, ease of use etc. that are non-tangible, and cannot be assigned a monetary value. It is important to capture such parameters in a cost-benefit analysis.

In this thesis, the tangible as well as non-tangible costs and benefits are captured in a common model. Traditional comparison in monetary terms is not sufficient for this. Therefore a more applicable form of measurement, utilities-based measurement, is used. For the list of ilities selected in Chapter 3, two of them (affordability and usability) are further deconstructed to demonstrate the model presented in Chapter 3. The remaining ilities and completion of the analysis are future work. The three different options for display interfaces considered are the ones identified in Chapter 4, which are 1) video wear, 2) handheld (micro PC) and 3) tablet PC

5.2 Utility of Affordability – Individual Weights

To calculate the individual weights among the various attributes, the AHP process explained in Chapter 3 is used. For the purpose of comparing between two attributes, a 1-5 scale of comparison is proposed in Chapter 3. The comparisons can take the following values:

Equally important	1
Moderately important	2
Strongly important	3
Very strongly important	4
Extremely important	5

Among the three attributes of affordability (acquisition, development and operations) the preferences of the various attributes are assumed as follows:

- Development is equally important over operations
- Acquisition is strongly important over development
- Acquisition is moderately important over operations

The order of the three attributes is 1) acquisition, 2) development and 3) operations. The eigenvalue matrix as stated in Chapter 3 is used here for comparing the attributes. A 3 x 3 matrix is required for comparing three attributes. The 3 x 3 eigenvalue matrix for the preferences stated above takes the following form:

$$[A]_{3x3} = \begin{bmatrix} 1.0 & a_{12} & a_{13} \\ a_{21} & 1.0 & a_{23} \\ a_{31} & a_{32} & 1.0 \end{bmatrix}$$

Here a_{12} refers to comparing acquisition over development. Similarly, a_{32} refers to comparing operations over development. Based on the preferences of the attributes, the pair-wise comparison of the attributes would be as follows

$$= \begin{bmatrix} 1.0 & 0.5 & 1.5 \\ 2.0 & 1.0 & 3.0 \\ 1.5 & 0.25 & 1.0 \end{bmatrix}$$

The normalized matrix is determined by dividing the values in each column by the sum of the column:

$$= \begin{bmatrix} 0.15 & 0.29 & 0.23 \\ 0.54 & 0.57 & 0.62 \\ 0.27 & 0.14 & 0.15 \end{bmatrix}$$

Now, the eigenvector is formed as the average of each normalized row:

$$[W]_{3x1} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} 0.23 \\ 0.58 \\ 0.19 \end{bmatrix}$$

Finally, the eigenvector is the weights of the three attributes using the AHP model where the weights of all the attributes sum to 1. The different weights are

- Weight (Acquisition costs/Overhead savings) = 0.23
- Weight (Development cost/Productivity increase) = 0.58
- Weight (Operations costs/Maintenance savings) = 0.19

These weights, along with the individual utilities calculated in the previous section, are taken together in the next section for calculating the final utility using the additive utility function.

5.3 Utility for Affordability

Affordability has the following attributes: acquisition costs/overhead savings, development costs/productivity increase, and operations cost/maintenance savings. All of these attributes are measurable in monetary terms. As discussed previously, in order to calculate the utility for affordability for the various display interface options of the MAT, the following steps are required.

1. Identify the cost functions and the benefit functions
2. Apply the cost and benefit functions to the life term of the project/system.
3. Calculate the Net Present Value (NPV) of the costs and benefits and calculate the cost-benefit ratio for each of the attributes under each option.
4. Calculate the individual utility values for each attribute using the cost-benefit ratio.
5. Using the individual weights of each attribute calculated with the AHP method, apply the additive utility function to get the weighted utility value for each option.

The first step in the process is the identification of cost and benefit functions. In calculating the costs and benefits, a time period of 10 years is considered as the life period required of the MAT. The three different display interfaces have three different life terms. The tablet PC is assumed to have to life span of 5 years, the handheld is assumed to have a lifespan of 4 years, and the video wear is assumed at 3 years of lifespan. The interest rate considered here is 7%. It is the recommended rate by the government currently for calculating present value. The various steps in the analysis are:

- Identification of cost and benefit functions
- Calculating the Net Present Value (NPV) of costs and benefits
- Comparison of all the options on the basis of benefit vs. costs ratio
- Sensitivity Analysis to verify the results in the previous step

Each of these steps is explained in detail

5.3.1 Cost function

The cost function for the display interface of MAT is as follows:

Life Cycle Costs = Initial Startup Cost (research and development) +
Acquisition Cost (cost of hardware/software) +
Development Cost (implementation & integration) +
Operations Cost (resource burden on the system, support services, supplies, personal) +
Maintenance Cost (personal, training, equipment and system maintenance)

The life cycle costs are calculated for the tablet PC option with reference to data from Information Technology (IT) implementation projects. For the other two options, handheld and video wear, proportional numbers are considered taking the tablet PC as the reference. The proportional numbers are considered with the assumption that similar project implementation with the handheld and video wear would cost proportionally higher or lower than the cost of implementation with tablet PC. Since the real numbers for handheld and video wear are not known, proportional costs assumed are 1:1 for handheld and 1:3 for video wear. The handhelds are assumed to cost 1.5 times more in development in comparison to tablet PC and 0.75 times in operations and maintenance. The video wears are assumed to cost 3 times more spread across the different attributes. The decision makers can vary the assumptions to see the effect on the overall cost and benefit for the various options. The life cycle costs for the three options are shown in Appendix F.1. All the values are in US dollars.

5.3.2 Benefit functions

The benefit function for the display interface of the MAT is as follows:

Life Time Benefits = Overhead Savings (direct and indirect) +
Productivity Increase (increase in mission and operator efficiency)
+ Maintenance Savings (health & safety maintenance savings)

Similar to the life cycle costs, the lifetime benefits are calculated for the tablet PC option with reference to data from medium scale IT implementation projects for the Government. The other two options are also proportionally-based as before.

The lifetime benefits for the three options are shown in Appendix F.2. All values are in US dollars.

5.3.3 Discounted Cost-benefits

Cost-benefit analysis puts all relevant costs and benefits in present-value terms. An appropriate discount rate is chosen to compute all relevant future costs and benefits in present value terms. The discount rate is based on the future cash flow in lieu of the present value of the cash flow. Typically, it is based on the government bond rate.

Because the costs and benefits are spread over a period of 10 years for he displays, they have to be discounted to bring it to present terms. The discount rate used is 7 % in compliance with the US Government recommended discount rate. Appendix F.3 shows the discounted cost and benefit values for all the three options. Looking at the discounted cost-benefit values, only the tablet PC option has a positive NPV value, which means that decision makers looking at only the NPV calculation for decision making would consider only the tablet PC option.

5.3.4 Comparison of all the options

Based on the discounted costs and benefits calculated in the previous step, the comparison of the cumulative costs and benefits is represented in Figure 14.

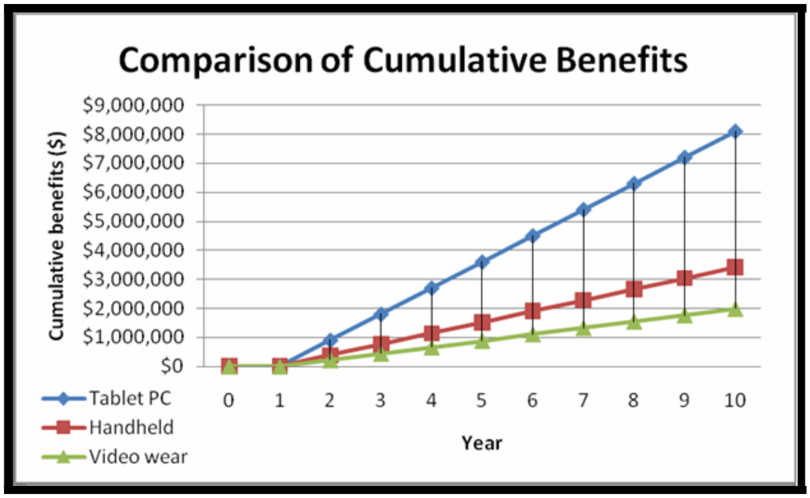


Figure 14: Comparison of cumulative benefits

Plotting the net of benefits – costs shows that other than the tablet PC, the rest of the options have negative NPV over the life term of the MAT (Figure 15).

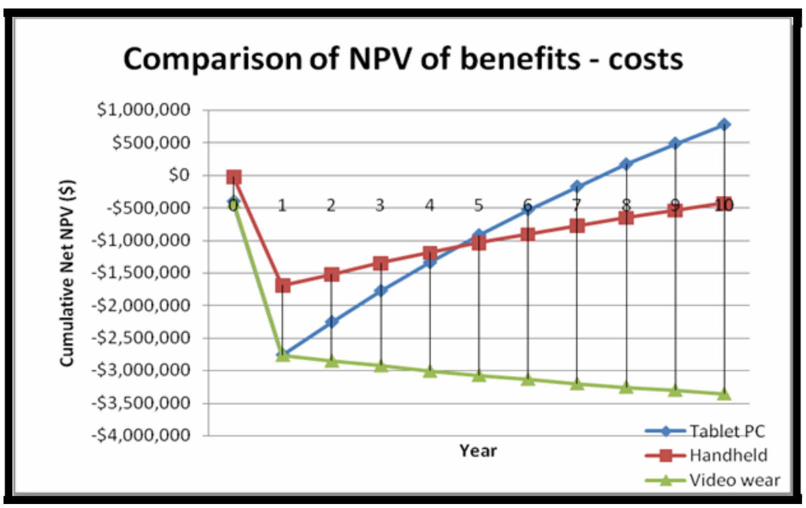


Figure 15: Comparison of NPV of cost-benefit

The comparison of the overall costs and benefits and the benefit to cost ratio is as follows

Table 5: Comparison of discounted costs and benefits

Alternative	Discounted Cost	Discounted Benefit	Discounted Net	Benefit to Cost Ratio
Tablet PC	$4,698,691	$5,480,102	$781,411	1.17
Handheld	$2,743,425	$2,313,821	-$429,605	0.84
Video wear	$4,698,691	$1,339,580	-$3,359,110	0.29

For the analysis of the proposed model, the various attributes of the '-ility' are compared side by side for the various options. These values are used later for the utility calculation.

Table 6: Comparison of the benefit-cost ratio across different attributes

Cost-Benefit Ratio			
	Cost-Benefit ratio of different displays		
Display Type	**Acquisition**	**Development**	**Operations**
Tablet PC	16.59	3.26	0.36
Handheld	5.07	0.87	0.40
Video wear	0.68	0.33	0.14

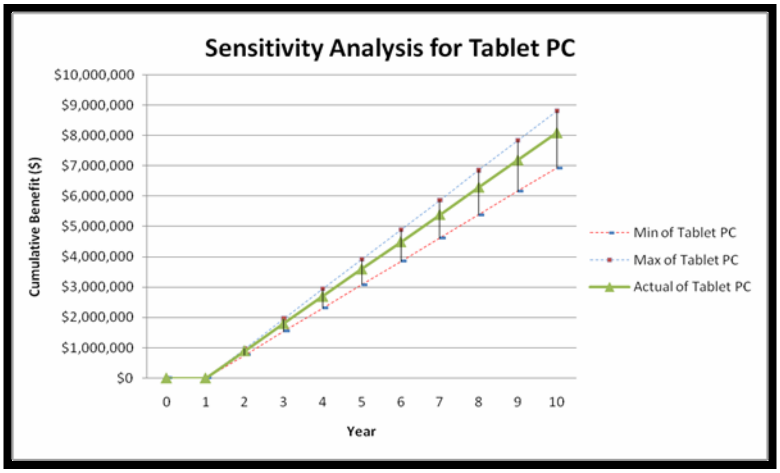
From this table, the tablet PC has higher benefits then the other options for most of the cost factors. One aspect to consider is the variation of the results if one or more parameters in the cost and benefit function varies. To consider such variations, a sensitivity analysis is performed.

5.3.5 Sensitivity Analysis

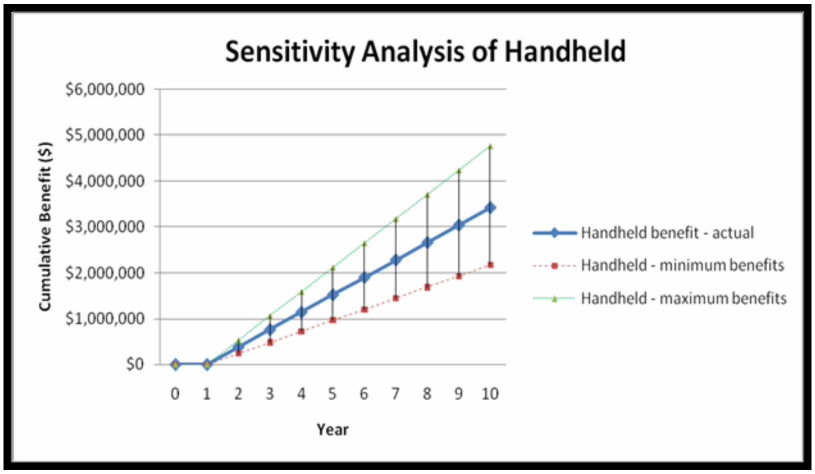
The objective of sensitivity analysis is to identify those critical inputs in the model whose variability affects the results. This is particularly important because if, for example, a change of 5% in one of the parameters changes the results such that the ranking of the options changes, then the decision makers need to know. The pictorial representation of the sensitivity analysis of the three different options is shown in Figure 16 a, b and c. The sensitivity analysis graphs in Figure 17 shows the net cumulative benefit (net benefit – net cost accumulated over the years) when the net cumulative costs are varied. The maximum and the minimum possible costs are based on assumptions made for this thesis. The range remains the same for all the options. Appendix F.5 shows the minimum and maximum costs that were applied for all the parameters in the cost function.

The sensitivity analysis of the three display options shows the variability in the benefit when the costs vary. It can be seen that the variability of the display interfaces is much less for the tablet PC in comparison to the other two options of handheld device and video wear.

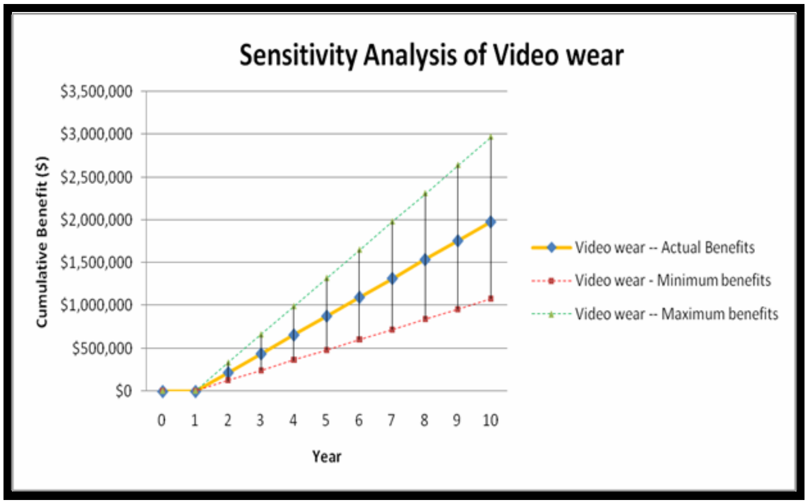
The results of the sensitivity analysis validate the conclusions drawn that the tablet PC provides the highest benefit among the different options. This is because the variability of



a. Sensitivity analysis of the tablet PC



b. Sensitivity analysis of the handheld



c. Sensitivity analysis of video wear

Figure 16 a, b, c : Sensitivity analysis of the net cumulative benefit from various options

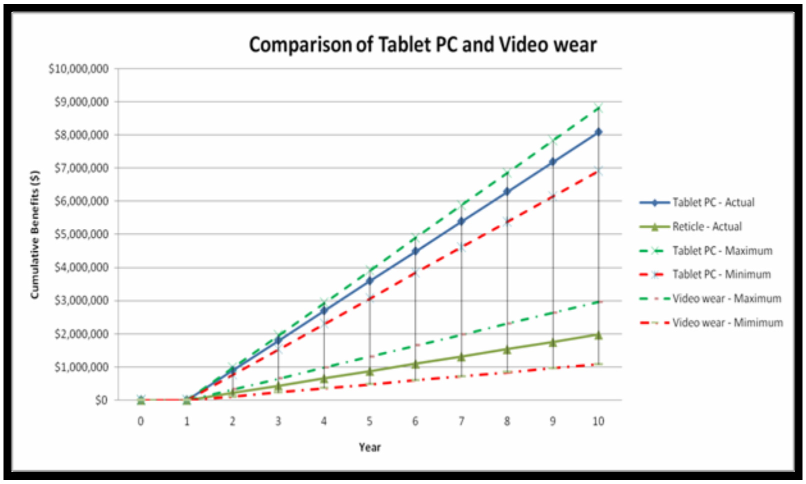


Figure 17: Comparison of the sensitivity analysis of net benefit for tablet PC and video wear

net benefits in the sensitivity analysis is much less for the tablet PC then it is for the handheld or video wear. If the variability is less, it means that if the costs over the years do not change significantly, the expected benefits would also not increase or decrease dramatically.

The cost-benefit ratios of the three options give the basis for utility calculation. A part of the proposed methodology is to convert the results of comparison into individual utilities. The next section shows how the cost-benefit ratios across different attributes of affordability are converted into individual utilities.

5.4 Utility of Affordability

For each of the various display form options of the MAT, the individual utility is calculated for affordability. The benefit-cost ratios from Table 6 are used to calculate the individual utility. The proportional score method (shown below) of calculating utility is used to have the individual utilities on the same scale.

$\text{Utility}_i(x)$ = (x – Worst Value) /(Best Value – Worst Value)

Here, subscript i is the attribute for which utility is to be calculated, x is the benefit-cost ratio value for that attribute, 'Worst Value' is the lowest benefit cost ratio value in the entire table, and 'Best Value' is the highest benefit-cost ratio value in Table 6. Based upon the benefit cost values obtained in Table 6, the corresponding utility values for the various combinations of attributes and display options are as follows:

- $\text{Utility}_{\text{Handheld}}$ (Acquisition) = (5.07 - .14)/(16.59 – 0.14) = 0.29
- $\text{Utility}_{\text{Handheld}}$ (Development) = (0.87 - .14)/(16.59 – 0.14) = 0.04
- $\text{Utility}_{\text{Handheld}}$ (Operations) = (0.40 - 0.14)/(16.59 – 0.14) = 0.012
- $\text{Utility}_{\text{Tablet PC}}$ (Acquisition) = (16.59 - 0.14)/(16.59 – 0.14) = 1

- Utility $_{Tablet\ PC}$ (Development) = (3.26 - 0.14)/(16.59 – 0.14) = 0.19
- Utility $_{Tablet\ PC}$ (Operations) = (0.36 - 0.14)/(16.59 – 0.14) = 0.013
- Utility $_{Video\ wear}$ (Acquisition) = (0.68 - 0.14)/(16.59 – 0.14) = 0.033
- Utility $_{Video\ wear}$ (Development) = (0.33 - 0.14)/(16.59 – 0.14) = 0.012
- Utility $_{Video\ wear}$ (Operations) = (0.14 - .14)/(16.59 – 0.14) = 0.00

These are the individual utility values for the various attributes categorized under various options. The next step in the proposed model is to calculate the individual weights. The following section explains the calculation of individual weights for each attribute.

5.5 Utility of Affordability – Additive Utility

The weighted utility function for the three attributes of acquisition, development and operations is represented by the equation below:

Utility $_i$ (Acquisition, Development, Operations) = Weight (Acquisitions) * Utility $_i$ (Acquisitions) + Weight (Development) * Utility $_i$ (Development) + Weight (Operations) * Utility $_i$ (Operations)

Here subscript i represent the various available options: tablet PC, handheld and video wear. Based on this additive utility function, the utility of the various options is as follows:

- Utility $_{Handheld}$ (Acquisition, Development, Operations) = 0.23 * 0.29 + 0.58 * .04 + 0.19 * 0.012 = 0.1
- Utility $_{Tablet\ PC}$ (Acquisition, Development, Operations) = 0.23 * 1 + 0.58 * 0.19 + 0.19 * 0.013 = 0.34
- Utility $_{Video\ wear}$ (Acquisition, Development, Operations) = 0.23 * 0.033 + 0.58 * 0.012 + 0.19 * 0.0 = 0.015

Therefore, the costs and benefits obtained in the earlier sections have been converted to equivalent utility values. The utility values of affordability for the various display options are as follows:

- Utility $_{Handheld}$ (Affordability) = 0.1
- Utility $_{Tablet\ PC}$ (Affordability) = 0.34
- Utility $_{Video\ wear}$ (Affordability) = 0.015

In the following section, the model is applied to calculate the utility of another '-ility', usability. The experimental results obtained in Chapter 4 are used in the utility calculation.

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5.6 Utility for Usability – Individual Weights

Between the two attributes of usability (movement time and index of performance), the preference of the attributes based on research data is as follows:

- Index of performance is strongly important over movement time
- Movement time is not as important as index of performance

The order of the two attributes is 1) index of performance and 2) movement time. Using the AHP model described in Chapter 3, the eigenvalue matrix is used for comparing the attributes. Since there are two attributes, a 2 x 2 matrix is required for comparing them. The eigenvalue matrix [B] takes the following form:

$$[B]_{2\times 2} = \begin{bmatrix} 1.0 & a_{12} \\ a_{21} & 1.0 \end{bmatrix}$$

Here a_{12} refers to comparing index of performance over movement time. Similarly, a_{21} refers to comparing movement time over index of performance. Based on the preferences of the attributes, the pair wise comparison of the attributes would be as follows

$$= \begin{bmatrix} 1.0 & 3 \\ 0.5 & 1.0 \end{bmatrix}$$

The normalized matrix is determined by dividing the values in each column by the sum of the column:

$$= \begin{bmatrix} 0.67 & 0.75 \\ 0.33 & 0.25 \end{bmatrix}$$

Now, the eigenvector is formed as the average of each normalized row:

$$[W]_{2\times 1} = \begin{bmatrix} W_1 \\ W_2 \end{bmatrix} = \begin{bmatrix} 0.71 \\ 0.29 \end{bmatrix}$$

Finally, the eigenvector is the weights of the three attributes. The different weights are

- Weight (Index of Performance) = 0.71
- Weight (Movement Time) = 0.29

These weights along with the individual utilities calculated in the next section are taken together for calculating the final utility using the additive utility function.

5.7 Utility of Usability

The results from the experiment on usability detailed in Chapter 4 are used for calculating the utility of usability. The attributes of usability that are considered here are movement time and index of performance as shown in Table 7.

Table 7: Attributes of usability for the different options

	Movement Time	Index of Performance
Tablet PC	20.74	0.089
Handheld	23.36	0.085
Video wear	32.05	0.074

The user preference for the various options is shown in the table below. The number in the cell indicates the number of subjects who preferred this option. If a cell is blank, it indicates that no one has preferred that option.

Table 8: Subjects' preference for the various display options

	Very useful	Somewhat useful	Useful	Partially useful	Not at all useful
The standard Tablet PC with mouse input	3	2	1		
The standard Tablet PC with touch screen input	2	3	1		
The ICuiti video wear display with mouse input		1	2	2	1
The micro PC with touch screen input	1	2	2		1
The micro PC with mouse input		2	1	3	

The preferences of the subjects are evenly distributed and it can be said that tablet PC was found to be more useful regardless of the input device.

5.8 Utility of Usability – Individual Utility

The movement times and indices of performance from Table 7 are converted to equivalent individual utility values. Similar to calculating the utility of affordability, the proportional score method is used. The equation below shows the proportional score method

$\text{Utility}_i(x) = (x - \text{Worst Value}) / (\text{Best Value} - \text{Worst Value})$

Here, i is the attribute for which utility is to be calculated, x is either the movement time or the index of performance value for that attribute. 'Worst Value' is the lowest movement time value or index of performance value in the entire table, and 'Best Value' is the highest movement time value or index of performance value in Table 7. Based upon the movement time and index of performance values obtained in Table 7, the corresponding utility values for the various combinations of attributes and display options are as follows:

- Utility $_{Handheld}$ (Movement Time) = (23.36 - 32.05)/(20.74 – 32.05) = 0.76
- Utility $_{Handheld}$ (Index of Performance) = (0.085 - 0.074)/(0.089 – 0.074) = 0.73
- Utility $_{Tablet\ PC}$ (Movement Time) = (20.74 - 32.05)/(20.74 – 32.05) = 1
- Utility $_{Tablet\ PC}$ (Index of Performance) = (0.089 - 0.074)/ (0.089 – 0.074) = 1
- Utility $_{Video\ wear}$ (Movement Time) = (32.05 - 32.05)/(20.74 – 32.05) = 0.0
- Utility $_{Video\ wear}$ (Index of Performance) = (0.074 - 0.074)/ (0.089 – 0.074) = 0.0

After calculating the individual utilities, the next step is the calculation of individual weights. The following section explains the calculation of individual weights for each attribute under usability.

5.9 Utility of Usability – Additive Utility

Similar to the final step in calculating the utility used in affordability, the weighted utility function is used. The weighted utility function is represented below:

Utility $_i$ (Index of Performance, Movement Time) = Weight (Index of Performance) * Utility $_i$ (Index of Performance) + Weight (Movement Time) * Utility $_i$ (Movement Time)

Here subscript i represent the various available options including tablet PC, handheld and video wear. Based on this additive utility function, the utility of the various options is as follows:

- Utility $_{Handheld}$ (Index of Performance, Movement Time) = 0.71 * 0.73 + 0.29 * .76 = 0.74
- Utility $_{Tablet\ PC}$ (Index of Performance, Movement Time) = 0.71 * 1 + 0.29 * 1 = 1
- Utility $_{Video\ wear}$ (Index of Performance, Movement Time) = 0.71 * 0.0 + 0.29 * 0.0 = 0.0

Therefore, the experimental result obtained in Chapter 4 is converted to equivalent utility values. The utility values of usability for the various display options are as follows:

- Utility $_{Handheld}$ (Usability) = 0.74
- Utility $_{Tablet\ PC}$ (Usability) = 1
- Utility $_{Video\ wear}$ (Usability) = 0.0

The results show that tablet PC has the best utility followed by handheld and then the video wear.

5.10 Overall utility value

So far, it is shown how to calculate the utility of the individual '-ilities' for each of the options. The ultimate goal is to get a utility value for each option under consideration. To reach that goal, the following steps are required:

1. Calculate the utility of each display form for all its '-ilities'. Utility for two 'ilities' from the list (affordability and usability) is calculated in this chapter.
2. Calculate the relative weight of each of the utilities using the AHP model
3. Use the additive utility function to calculate the overall utility values under each display form.
4. Each display form will have one numeric value for its overall utility. The option with the highest overall utility value will be the recommended option.

Based on these , the calculation of the utility for the three options based on the utility values obtained for the two '-ilities' is as follows:

Step 1:
From sections 4 and 5

Utility of Affordability

- Utility $_{Handheld}$ (Affordability) = 0.1
- Utility $_{Tablet\ PC}$ (Affordability) = 0.34
- Utility $_{Video\ wear}$ (Affordability) = 0.015

Utility of Usability

- Utility $_{Handheld}$ (Usability) = 0.74
- Utility $_{Tablet\ PC}$ (Usability) = 1
- Utility $_{Video\ wear}$ (Usability) = 0.0

Step 2:
For this research, it is assumed that affordability is equally important over usability. Since both the attributes are equally important, the AHP model will generate the same weight for both the attributes. Therefore

- Weight (Affordability) = 0.5
- Weight (Usability) = 0.5

Step 3:
Using the additive utility function, the overall utility values are as follows:

- Overall Utility $_{Handheld}$ (Affordability, Usability) = 0.5 * 0.1 + 0.5 * .74 = 0.42
- Overall Utility $_{Tablet\ PC}$ Affordability, Usability) = 0.5 * 0.34 + 0.5 * 1 = 0.67
- Overall Utility $_{Video\ wear}$ (Affordability, Usability) = 0.5 * 0.015 + 0.5 * 0.0 = 0.01

Step 4:
So the order of utility is as follows, 1) tablet PC, 2) handheld and 3) video wear

Therefore, based on the calculation of two '-ilities', the recommendation is for the tablet PC option. However, more work is needed to calculate the utility of the rest of the '-ilities' and then calculate the overall utility to make the final recommendation. Moreover, the distance between the handheld and the tablet PC is much smaller than from the handheld to the Video wear, so more work is needed to develop appropriate sensitivity analysis tools. These aspects remain for future work.

5.11 Summary

This chapter shows the application of the proposed model for two different kinds of '-ilities', one is an objective '-ility' and the other is a subjective one. This approach can effectively bring both subjective and objective '-ilities' into a common model, and help decision makers early in the system acquisition decision process.

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6. Summary and Conclusion

This research had two objectives, 1) to develop a conceptual design for a decision support tool that aids a submarine mission commander in the management of multiple UUVs, and 2) to develop a method to objectively evaluate different displays in the conceptual design stage. The first objective was met with the conceptualization of the Mission Assistance Tool (MAT) as a decision support system. As a result, comprehensive functional and information requirements were generated that must be met in order to support effective human decision making.

Determining the physical form, based on the requirements in an objective, multi-dimensional manner, motivated the second primary focus of this research: the development of the display physical form cost-benefit model. The strength of the proposed cost-benefit analysis model lies in the fact that it takes into account both subjective and objective costs and benefits, and brings both of them into similar terms. As the cost-benefit analysis takes place after functional requirements are determined, the trade-offs in implementing the functionalities become clear.

From the requirements generation, the experiment, and cost-benefit analysis, the following conclusions can be drawn about the candidate display forms:

- The tablet PC also has the highest utility in terms of affordability
- The tablet PC has the highest utility in terms of usability
- The cost-benefit analysis of affordability used proportional numbers, which if not varied significantly, is unlikely to alter the results as evident from the sensitivity analysis
- If the life term of the MAT is taken as assumed, then only the tablet PC option has a positive NPV value for its net of benefits over costs. However, if the proportional numbers used here vary, then the handheld option would also have a positive NPV over the life time of the MAT system

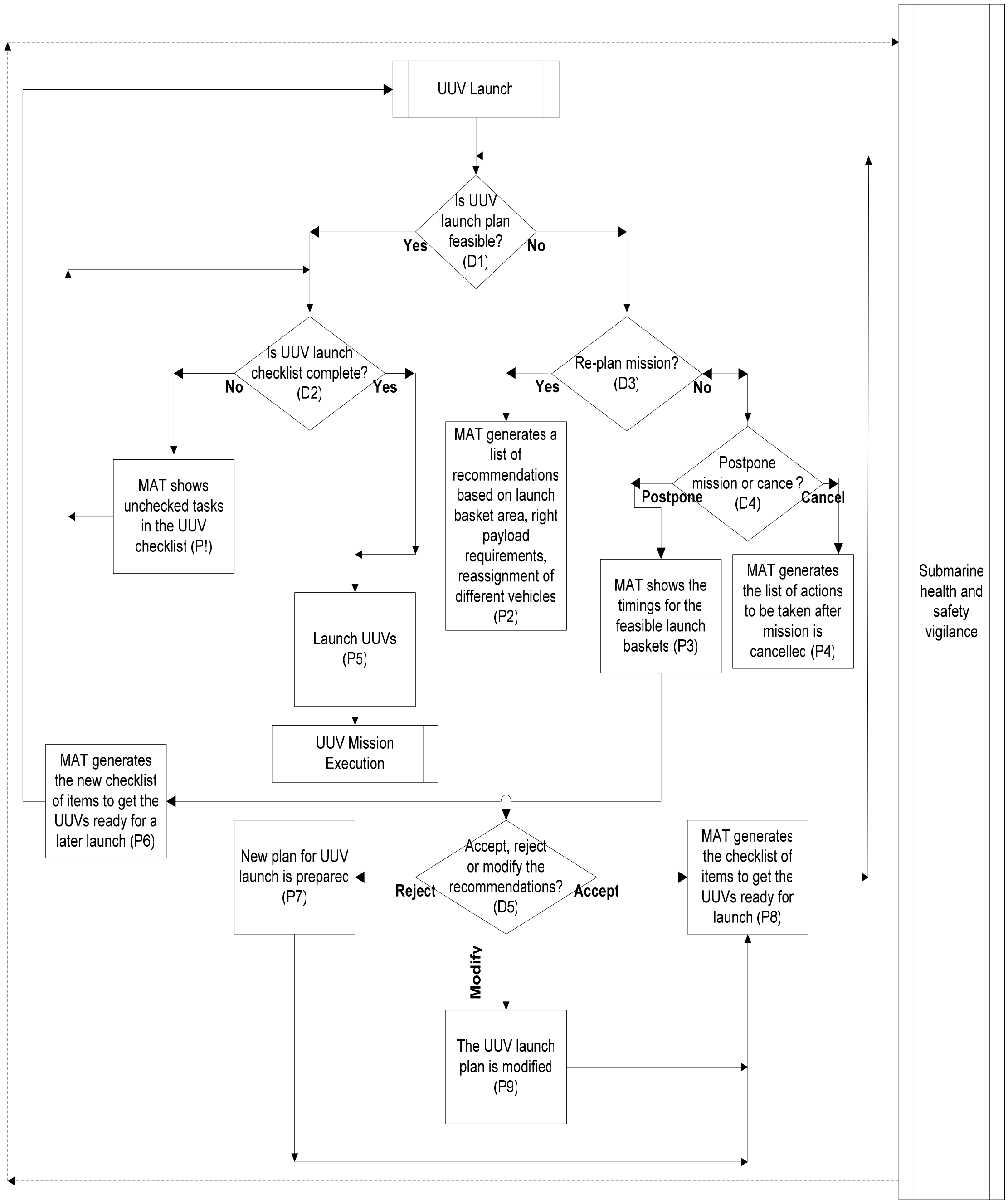
Given these results, the MAT display should take the form of a tablet PC. While this thesis demonstrates how Fitts' law can be used to measure objective usability, the results also demonstrate that the size of a display alone cannot determine user performance. The display must be considered along with the input mechanism in order to determine the user performance in task execution.

6.1 Future work

While this thesis achieves the objectives sought for the initial conceptual design stage, future work is needed. The proposed cost-benefit analysis model was applied to only two '-ilities', so the model should be extended to the remaining relevant '-ilities' in order to obtain the final overall utility value for each of the display options. In addition, more complete sensitivity analysis methods need further development, particularly for usability. Finally, software prototypes for the MAT, given the ultimately selected physical form, should be designed.

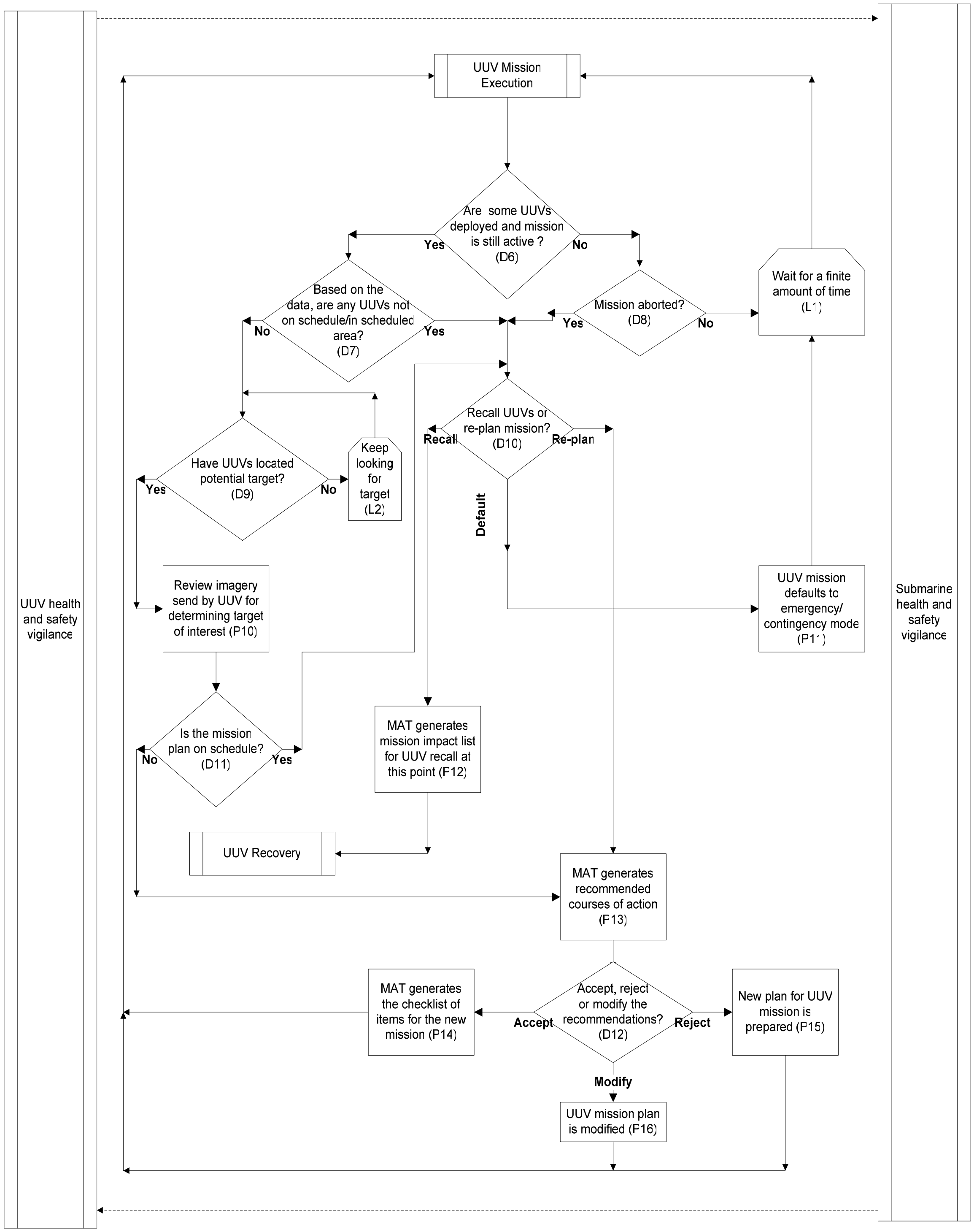
Appendix A.1

Event Flow Diagram: UUV Launch



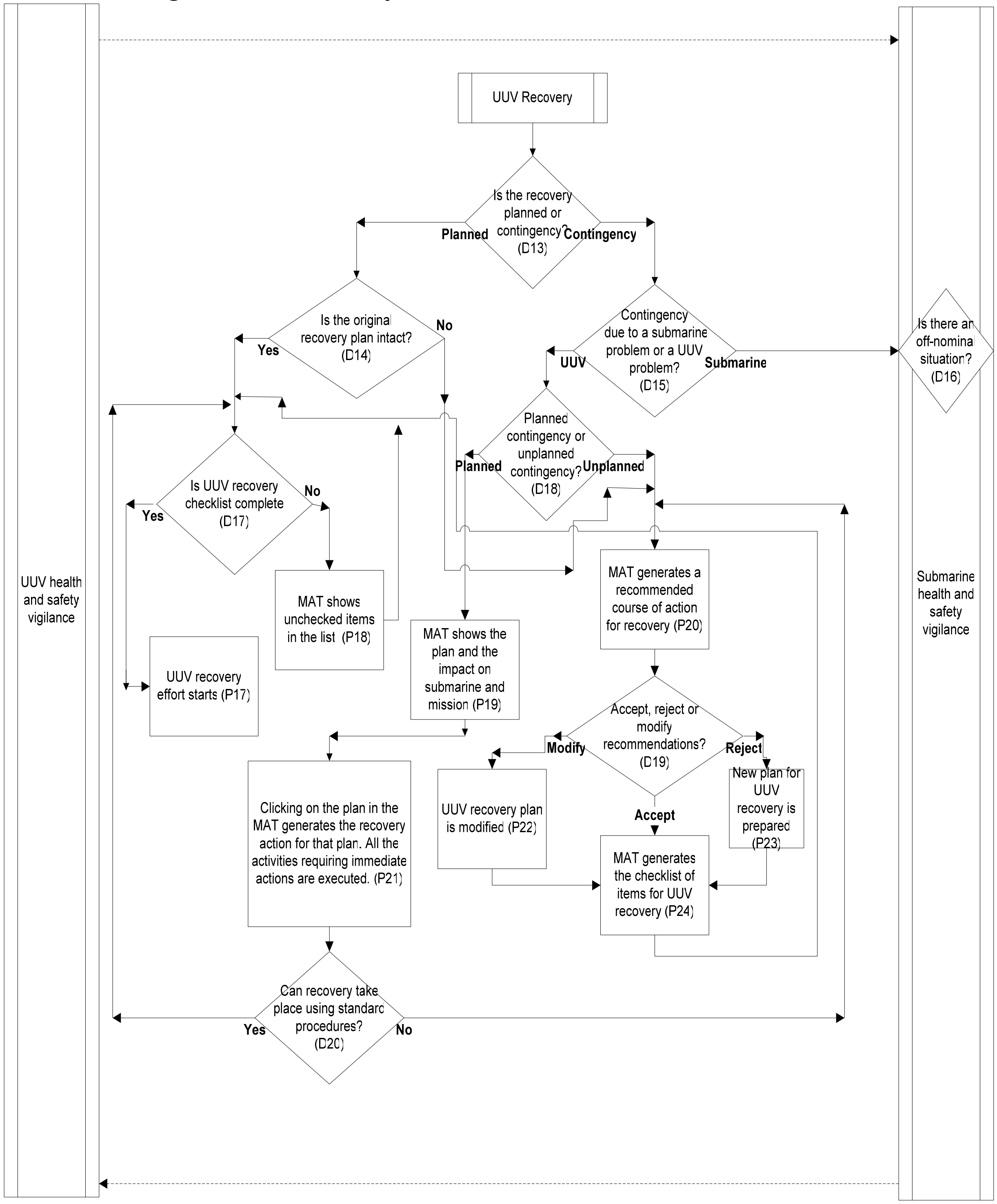
Appendix A.2

Event Flow Diagram: UUV Mission Execution



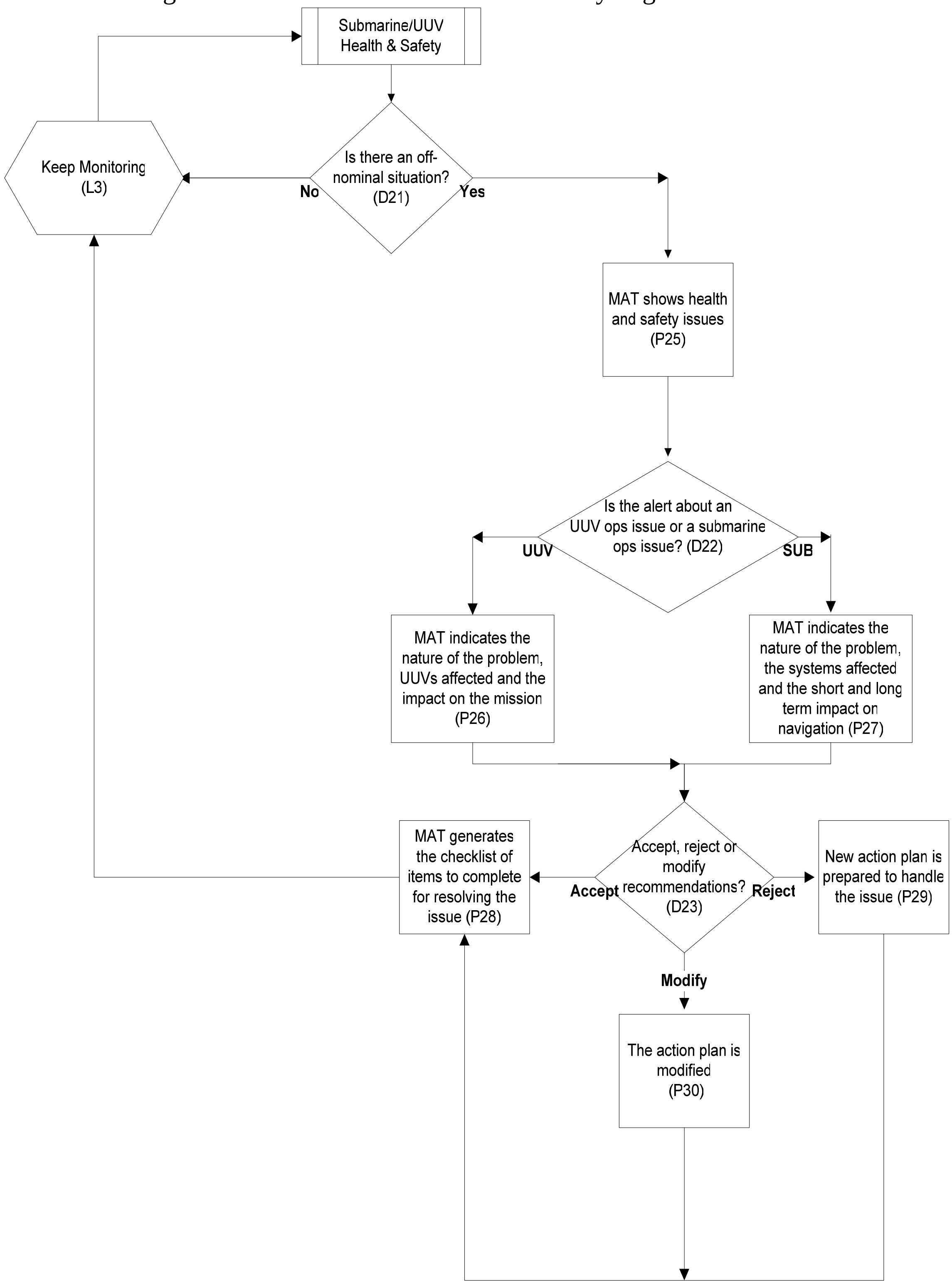
Appendix A.3

Event Flow Diagram: UUV Recovery



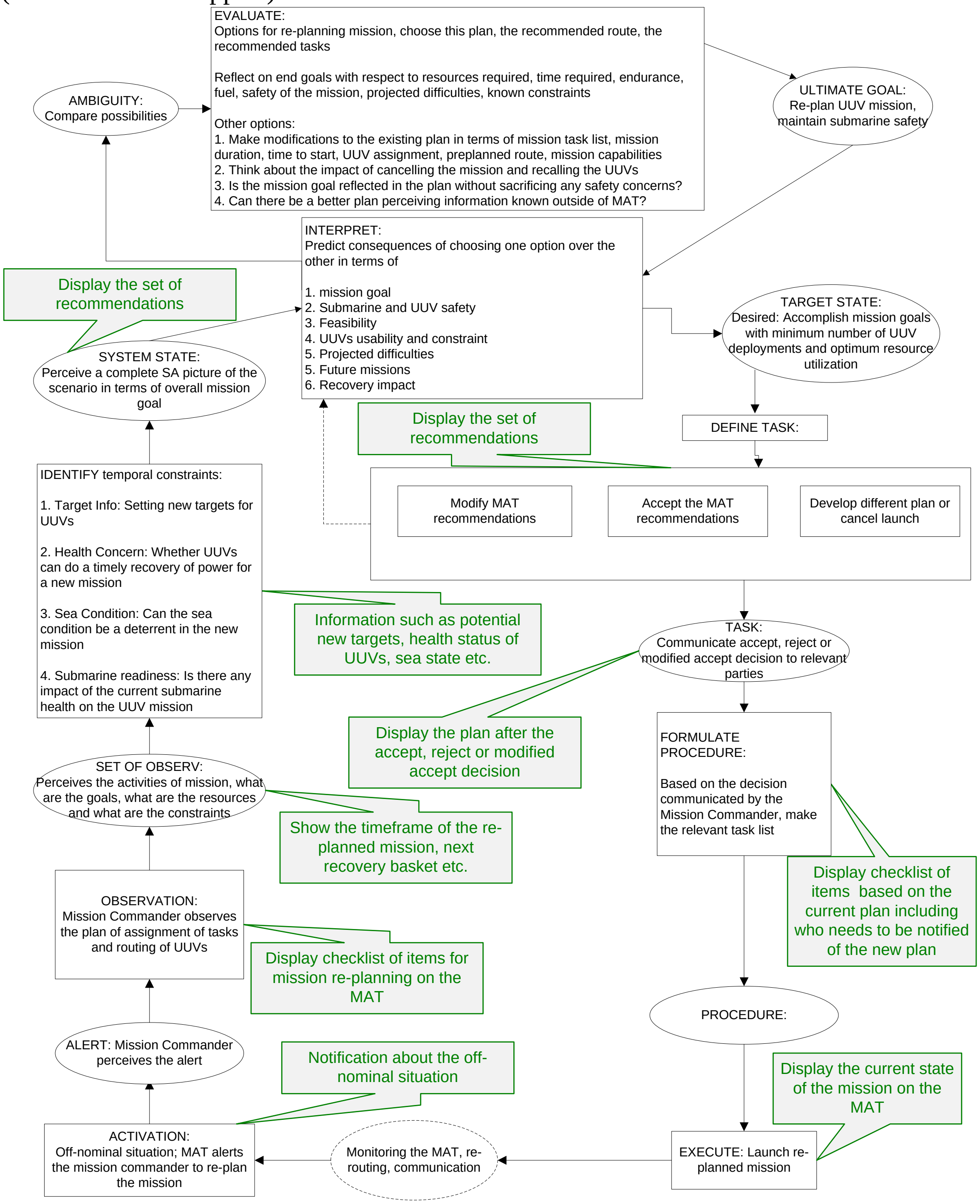
Appendix A.4

Event Flow Diagram: Submarine/UUV Health and Safety Vigilance



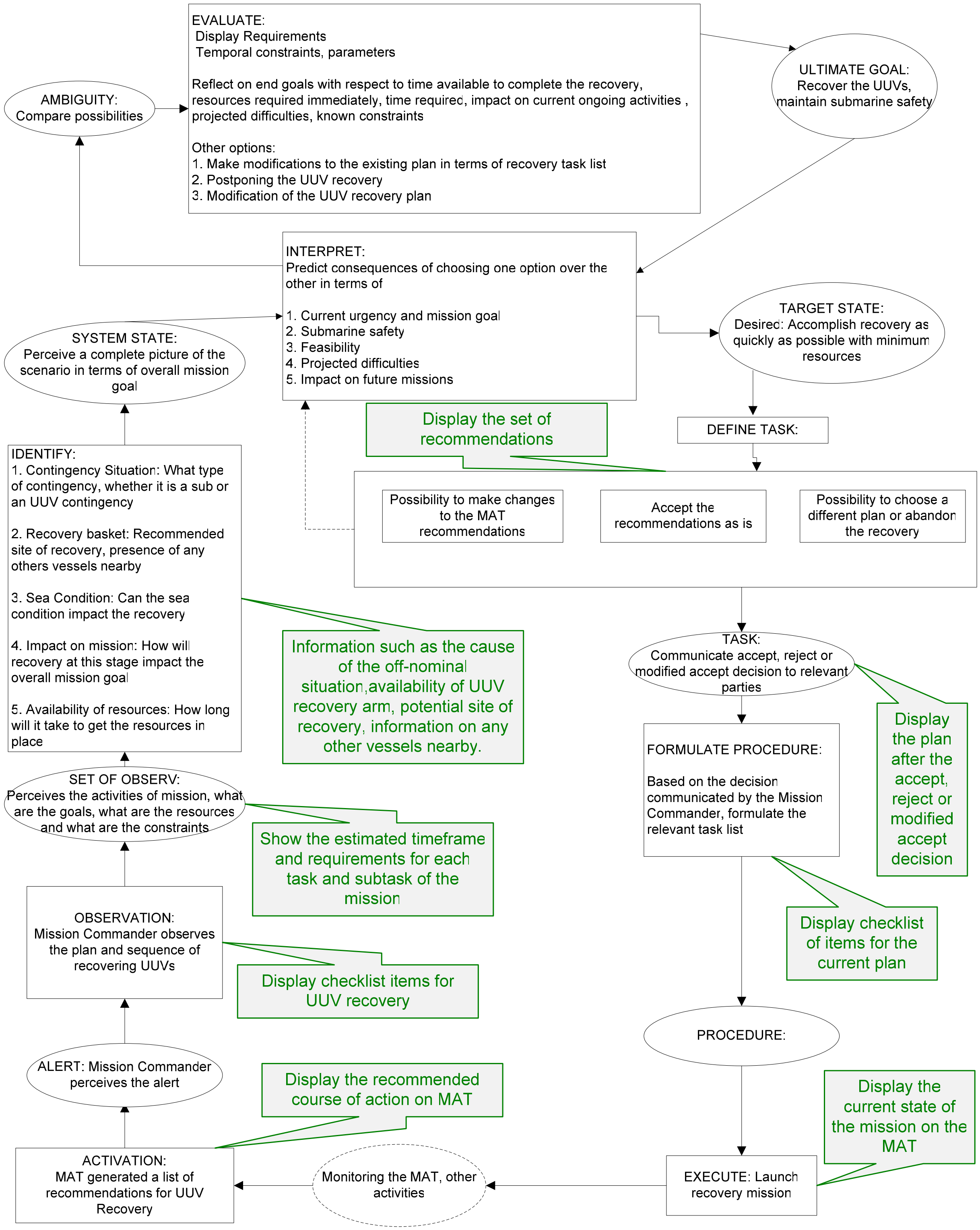
Appendix B.1

UUV Mission Execution Decision Ladder with corresponding display requirements: (MAT Decision Support)



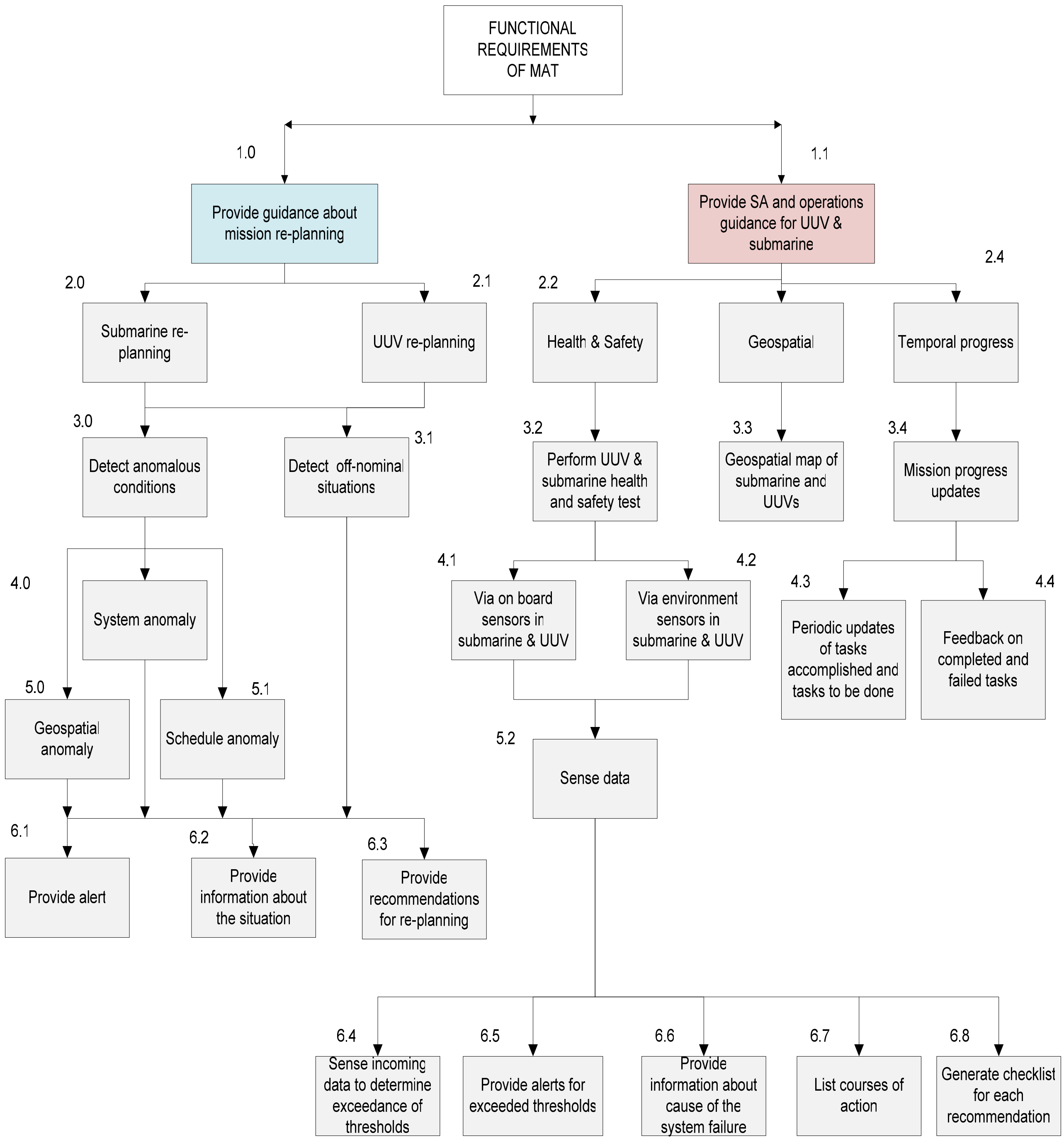
Appendix B.2

UUV Recovery Decision Ladder with corresponding display requirements: (MAT Decision Support)



Appendix C

High Level Functional Requirements



Appendix D

Document for capturing the results of the experiment

Subject Name:

Experiment: Map Pointing

Device form: Tablet PC

Sl. #	Screen size (mm)	Input device	Scenario name	Output File Name
1	245 x 185	Mouse	Training_cities_11	Fits_TabletMouse_1
2	245 x 185	Mouse	Training_cities_22	Fits_TabletMouse_2
3	245 x 185	Touch Pointing	Training_cities_11	Fits_TabletTP_1
4	245 x 185	Touch Pointing	Training_cities_22	Fits_TabletTP_2

Device form: Micro PC

Sl. #	Screen size (mm)	Input device	Scenario name	Output File Name
1	100 x 60	Mouse	Training_cities_11	Fits_MicroMouse_1
2	100 x 60	Mouse	Training_cities_22	Fits_MicroMouse_2
3	100 x 60	Touch Pointing	Training_cities_11	Fits_MicroTP_1
4	100 x 60	Touch Pointing	Training_cities_22	Fits_MicroTP_2

Device form: Icuiti VideoWear

Sl. #	Screen size (mm)	Input device	Scenario name	Output File Name
1	110 x 80	Mouse	Training_cities_11	Fits_Icuiti_1
2	110 x 80	Mouse	Training_cities_22	Fits_Icuiti_2

End of Experiment Survey

Question 1) What is your level of expertise using the stick pointer? No experience/Used before/Expert

Question 2) What is your experience level playing video games? No experience/Somewhat experienced/Expert

For the tasks you were given, please mark your opinion for each of the five devices using the categories given below:

	Very useful	Somewhat useful	Useful	Partially useful	Not at all useful
The standard tablet PC with mouse input					
The standard tablet PC with touch screen input					
The ICuiti video wear display with mouse input					
The micro PC with touch screen input					
The micro PC with mouse input					

Appendix E

Sample Data file format generated from experiment (Map pointing experiment)

Results for subject TabletT~1~SUBJECT~1

A	W	H	TH	(x, y)	HomeT	MoveT	E
503.91	363.22	78	44.92	(-0.88, -0.36)	2.89	24.37	0
433.19	1321.79	46	28.81	(1.06, 1.45)	3.28	19.28	1
989.77	67.53	23	42.48	(1.06, 0.36)	7.56	52.43	3
540.11	4764.83	71	65.35	(1.06, -0.73)	3.06	18.21	0
612.70	1304.45	57	56.50	(-0.18, -0.73)	2.84	20.12	0
787.54	298.67	73	32.79	(0.70, 0.36)	2.10	24.64	0
544.50	2036.47	34	31.58	(0.18, 0.18)	3.25	22.75	0
525.00	1626.50	29	40.68	(1.06, -0.18)	6.62	24.81	0
328.76	1580.37	35	25.46	(-0.18, 1.45)	1.78	24.06	0
403.87	380.67	21	37.68	(0.35, 0.36)	8.57	22.00	5

The data file is organized into rows and columns. Each row represents one individual map pointing task. The column headings are:

A	Amplitude (mm)
W	Width (mm)
H	Height
TH	Angle (Degrees)
(x,y)	The position, relative to the centre of the target, where the subject indicated the target city (mm)
E	Indicates the number of errors the subject committed for that task
HomeT	Homing time (ms)
MoveT	Moving time (ms)

With the values of A, W and MoveT, ID (Index of Difficulty) and IP (Index of Performance) are calculated.

Appendix F.1

Cost-Benefit Analysis: Life Cycle Costs

Note: Numerical values of costs for tablet PC are assumptions made with reference to the values in the report 'Cost-Benefit Analysis for NIH IT Projects' [12]. The values of costs for handheld and video wear are proportional values in reference to the ones of the tablet PC

Option I	Tablet PC					
Year	**Initial Startup**	**Acquisition Cost**	**Development Cost**	**Operations Cost**	**Maintenance Cost**	**Total**
	(R & D Cost)	(Cost of hardware/software)	(Implementation & Integration Cost)	(Resource burden on the system with support services, supplies, personal)	(Personal, training equipment and system maintenance)	
0	$10,000					$10,000
1		$100,000	$1,000,000	$200,000	$80,000	$1,380,000
2				$200,000	$60,000	$260,000
3				$200,000	$50,000	$250,000
4				$200,000	$40,000	$240,000
5				$200,000	$30,000	$230,000
6		$10,000		$200,000	$30,000	$240,000
7				$200,000	$30,000	$230,000
8				$200,000	$30,000	$230,000
9				$200,000	$30,000	$230,000
10				$200,000	$30,000	$230,000
Total	$10,000	$110,000	$1,000,000	$2,000,000	$410,000	$3,530,000
Option II	Handheld					
Year	**Initial Startup**	**Acquisition Cost**	**Development Cost**	**Operations Cost**	**Maintenance Cost**	**Total**
	(R & D Cost)	(Cost of hardware/software)	(Implementation & Integration Cost)	(Resource burden on the system including support services, supplies, personal)	(Personal, training equipment and system maintenance)	
0	$20,000					$20,000

1		$100,000	$1,500,000	$150,000	$40,000	$1,790,000
2				$150,000	$30,000	$180,000
3				$150,000	$20,000	$170,000
4				$150,000	$20,000	$170,000
5				$150,000	$20,000	$170,000
6		$10,000		$150,000	$20,000	$180,000
7				$150,000	$20,000	$170,000
8				$150,000	$20,000	$170,000
9				$150,000	$20,000	$170,000
10				$150,000	$20,000	$170,000
Total	$20,000	$110,000	$1,500,000	$1,500,000	$230,000	$3,360,000
Option III	Video wear					
Year	**Initial Startup**	**Acquisition Cost**	**Development Cost**	**Operations Cost**	**Maintenance Cost**	**Total**
	(R & D Cost)	(Cost of hardware/software)	(Implementation & Integration Cost)	(Resource burden on the system with support services, supplies, personal)	(Personal, training equipment and system maintenance)	
0	$400,000					$400,000
1		$200,000	$2,000,000	$250,000	$80,000	$2,530,000
2				$250,000	$70,000	$320,000
3				$250,000	$60,000	$310,000
4		$20,000		$250,000	$60,000	$330,000
5				$250,000	$60,000	$310,000
6				$250,000	$60,000	$310,000
7		$20,000		$250,000	$60,000	$330,000
8				$250,000	$60,000	$310,000
9				$250,000	$60,000	$310,000
10		$20,000		$250,000	$60,000	$330,000
Total	$400,000	$260,000	$2,000,000	$2,500,000	$630,000	$5,790,000

Appendix F.2

Cost-Benefit Analysis: Life Time Benefits

Note: Numerical values of benefits for tablet PC are assumptions made with reference to the values in the report 'Cost-Benefit Analysis for NIH IT Projects'[12]. The values of benefits for handheld and video wear are proportional values in reference to the values of the tablet PC

Option I	Tablet PC			
Year	**Overhead Savings**	**Productivity Increase**	**Maintenance Savings**	**Total**
	(Direct & Indirect Savings)	(Increase in mission efficiency and operator productivity)	(Health & Safety maintenance savings)	
0				$0
1				$0
2	$300,000	$500,000	$100,000	$900,000
3	$300,000	$500,000	$100,000	$900,000
4	$300,000	$500,000	$100,000	$900,000
5	$300,000	$500,000	$100,000	$900,000
6	$300,000	$500,000	$100,000	$900,000
7	$300,000	$500,000	$100,000	$900,000
8	$300,000	$500,000	$100,000	$900,000
9	$300,000	$500,000	$100,000	$900,000
10	$300,000	$500,000	$100,000	$900,000
Total	$2,700,000	$4,500,000	$900,000	$8,100,000
Option II	Handheld			
Year	**Overhead Savings**	**Productivity Increase**	**Maintenance Savings**	**Total**
	(Direct & Indirect Savings)	(Increase in mission efficiency and operator productivity)	(Health & Safety maintenance savings)	
0				$0
1				$0
2	$100,000	$200,000	$80,000	$380,000
3	$100,000	$200,000	$80,000	$380,000
4	$100,000	$200,000	$80,000	$380,000
5	$100,000	$200,000	$80,000	$380,000
6	$100,000	$200,000	$80,000	$380,000
7	$100,000	$200,000	$80,000	$380,000
8	$100,000	$200,000	$80,000	$380,000
9	$100,000	$200,000	$80,000	$380,000
10	$100,000	$200,000	$80,000	$380,000
Total	$900,000	$1,800,000	$720,000	$3,420,000

Option III	Video wear			
Year	**Overhead Savings**	**Productivity Increase**	**Maintenance Savings**	**Total**
	(Direct & Indirect Savings)	(Increase in mission efficiency and operator productivity)	(Health & Safety maintenance savings)	
0				$0
1				$0
2	$70,000	$100,000	$50,000	$220,000
3	$70,000	$100,000	$50,000	$220,000
4	$70,000	$100,000	$50,000	$220,000
5	$70,000	$100,000	$50,000	$220,000
6	$70,000	$100,000	$50,000	$220,000
7	$70,000	$100,000	$50,000	$220,000
8	$70,000	$100,000	$50,000	$220,000
9	$70,000	$100,000	$50,000	$220,000
10	$70,000	$100,000	$50,000	$220,000
Total	$630,000	$900,000	$450,000	$1,980,000

Appendix F.3

Discounted Cost-benefits

Note: The discounted cost-benefits are based on the costs and benefits outlined in Appendix F.1 and F.2. The discount rate applied here is 7% per annum applied at the end of the year.

OPTION I	Tablet PC					
Year	**Costs**	**Benefits**	**Discount Rate**	**Present Value of Cost(PVC)**	**Present Value of Benefit(PVB)**	**Net Present Value of Benefits - Costs**
	C	B	DR	C * DR	B * DR	PVB - PVC
0	$400,000	$0	1	$400,000	$0	-$400,000
1	$2,530,000	$0	0.93	$2,364,486	$0	-$2,364,486
2	$320,000	$900,000	0.87	$279,500	$786,095	$506,594
3	$310,000	$900,000	0.82	$253,052	$734,668	$481,616
4	$330,000	$900,000	0.76	$251,755	$686,606	$434,850
5	$310,000	$900,000	0.71	$221,026	$641,688	$420,662
6	$310,000	$900,000	0.67	$206,566	$599,708	$393,142
7	$330,000	$900,000	0.62	$205,507	$560,475	$354,967
8	$310,000	$900,000	0.58	$180,423	$523,808	$343,385
9	$310,000	$900,000	0.54	$168,619	$489,540	$320,921
10	$330,000	$900,000	0.51	$167,755	$457,514	$289,759
Total	$5,790,000	$8,100,000		$4,698,691	$5,480,102	$781,411
OPTION II	Handheld					
Year	**Costs**	**Benefits**	**Discount Rate**	**Present Value of Cost(PVC)**	**Present Value of Benefit(PVB)**	**Net Present Value of Benefits - Costs**
	C	B	DR	C * DR	B * DR	PVB - PVC
0	$20,000	$0	1	$20,000	$0	-$20,000
1	$1,790,000	$0	0.93	$1,672,897	$0	-$1,672,897
2	$180,000	$380,000	0.87	$157,219	$331,907	$174,688
3	$170,000	$380,000	0.82	$138,771	$310,193	$171,423
4	$170,000	$380,000	0.76	$129,692	$289,900	$160,208
5	$170,000	$380,000	0.71	$121,208	$270,935	$149,727
6	$180,000	$380,000	0.67	$119,942	$253,210	$133,268
7	$170,000	$380,000	0.62	$105,867	$236,645	$130,777
8	$170,000	$380,000	0.58	$98,942	$221,163	$122,222

9	$170,000	$380,000	0.54	$92,469	$206,695	$114,226
10	$170,000	$380,000	0.51	$86,419	$193,173	$106,753
Total	$3,360,000	$3,420,000		$2,743,425	$2,313,821	-$429,605
OPTION III	Video wear					
Year	**Costs**	**Benefits**	**Discount Rate**	**Present Value of Cost(PVC)**	**Present Value of Benefit(PVB)**	**Net Present Value of Benefits - Costs**
	C	B	DR	C * DR	B * DR	PVB - PVC
0	$400,000	$0	1	$400,000	$0	-$400,000
1	$2,530,000	$0	0.93	$2,364,486	$0	-$2,364,486
2	$320,000	$220,000	0.87	$279,500	$192,157	-$87,344
3	$310,000	$220,000	0.82	$253,052	$179,586	-$73,467
4	$330,000	$220,000	0.76	$251,755	$167,837	-$83,918
5	$310,000	$220,000	0.71	$221,026	$156,857	-$64,169
6	$310,000	$220,000	0.67	$206,566	$146,595	-$59,971
7	$330,000	$220,000	0.62	$205,507	$137,005	-$68,502
8	$310,000	$220,000	0.58	$180,423	$128,042	-$52,381
9	$310,000	$220,000	0.54	$168,619	$119,665	-$48,954
10	$330,000	$220,000	0.51	$167,755	$111,837	-$55,918
Total	$5,790,000	$1,980,000		$4,698,691	$1,339,580	-$3,359,110

Appendix F.4

Overall Cost-benefit ratio

Note: The overall cost-benefits are based on the costs and benefits outlined in Appendix F.1 and F.2.

Overall Cost-benefit				
Relative Value Comparison				
Alternative	Discounted Cost	Discounted Benefit	Discounted Net	Benefit to Cost Ratio
Tablet PC	$4,698,691	$5,480,102	$781,411	1.17
Handheld	$2,743,425	$2,313,821	-$429,605	0.84
Video wear	$4,698,691	$1,339,580	-$3,359,110	0.29

Cost-benefit ratio based of the different attributes

Benefit - Cost Ratio			
	Benefit cost Ratio of different displays		
Display Type	**Acquisition**	**Development**	**Operations**
Tablet PC	16.59	3.26	0.36
Handheld	5.07	0.87	0.40
Reticle	0.68	0.33	0.14

Appendix F.5

Sample of the sensitive analysis for the option of tablet PC

Note: The sensitivity analysis is based on the costs and benefits outlined in Appendix F.1 and F.2. The min and max values of costs shown below are assumptions made for this thesis.

Parameters	Range					
	Min - Max					
Development Cost	$500,000 - $2,500,000					
Operations Cost	$100,000 - $500,000					
Maintenance Cost	$20,000 - $100,000					
Minimum Cost	OPTION I Tablet PC					
Year	**Initial Startup**	**Acquisition Cost**	**Development Cost**	**Operations Cost**	**Maintenance Cost**	**Total Cost**
	(R & D Cost)	(Cost of hardware/software)	(Implementation & Integration Cost)	(Resource burden on the system with support services, supplies, personal)	(Personal, training equipment and system maintenance)	
0	$10,000					$10,000
1		$100,000	$500,000	$100,000	$60,000	$760,000
2				$100,000	$40,000	$140,000
3				$100,000	$20,000	$120,000
4				$100,000	$20,000	$120,000
5				$100,000	$20,000	$120,000
6		$10,000		$100,000	$20,000	$130,000
7				$100,000	$20,000	$120,000
8				$100,000	$20,000	$120,000
9				$100,000	$20,000	$120,000
10				$100,000	$20,000	$120,000
Total	$10,000	$110,000	$500,000	$1,000,000	$260,000	$1,880,000
Benefit with minimum cost						
Year	**Overhead Savings**	**Productivity Increase**	**Maintenance Savings**	**Total**	**Cumulative**	
	(Direct & Indirect Savings)	(Increase in mission efficiency and operator	(Health & Safety maintenance savings)			

		productivity)				
0				$0	$0	
1				$0	$0	
2	$300,000	$400,000	$70,000	$770,000	$770,000	
3	$300,000	$400,000	$70,000	$770,000	$1,540,000	
4	$300,000	$400,000	$70,000	$770,000	$2,310,000	
5	$300,000	$400,000	$70,000	$770,000	$3,080,000	
6	$300,000	$400,000	$70,000	$770,000	$3,850,000	
7	$300,000	$400,000	$70,000	$770,000	$4,620,000	
8	$300,000	$400,000	$70,000	$770,000	$5,390,000	
9	$300,000	$400,000	$70,000	$770,000	$6,160,000	
10	$300,000	$400,000	$70,000	$770,000	$6,930,000	
Total	$2,700,000	$3,600,000	$630,000	$6,930,000		
Maximum Cost	OPTION I Tablet PC					
Year	**Initial Startup**	**Acquisition Cost**	**Development Cost**	**Operations Cost**	**Maintenance Cost**	**Total Cost**
	(R & D Cost)	(Cost of hardware/software)	(Implementation & Integration Cost)	(Resource burden on the system with support services, supplies, personal)	(Personal, training equipment and system maintenance)	
0	$10,000					$10,000
1		$100,000	$2,500,000	$500,000	$100,000	$3,200,000
2				$500,000	$80,000	$580,000
3				$500,000	$70,000	$570,000
4				$500,000	$60,000	$560,000
5				$500,000	$60,000	$560,000
6		$10,000		$500,000	$60,000	$570,000
7				$500,000	$60,000	$560,000
8				$500,000	$60,000	$560,000
9				$500,000	$60,000	$560,000
10				$500,000	$60,000	$560,000
Total	$10,000	$110,000	$2,500,000	$5,000,000	$670,000	$8,290,000
Benefit with maximum cost						
Year	**Overhead Savings**	**Productivity Increase**	**Maintenance Savings**	**Total**	**Cumulative**	

	(Direct & Indirect Savings)	(Increase in mission efficiency and operator productivity)	(Health & Safety maintenance savings)			
0				$0	$0	
1				$0	$0	
2	$300,000	$600,000	$80,000	$980,000	$980,000	
3	$300,000	$600,000	$80,000	$980,000	$1,960,000	
4	$300,000	$600,000	$80,000	$980,000	$2,940,000	
5	$300,000	$600,000	$80,000	$980,000	$3,920,000	
6	$300,000	$600,000	$80,000	$980,000	$4,900,000	
7	$300,000	$600,000	$80,000	$980,000	$5,880,000	
8	$300,000	$600,000	$80,000	$980,000	$6,860,000	
9	$300,000	$600,000	$80,000	$980,000	$7,840,000	
10	$300,000	$600,000	$80,000	$980,000	$8,820,000	
Total	$2,700,000	$5,400,000	$720,000	$8,820,000		

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