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Making Decisions About Safety in US Ports and Waterways

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The US Coast Guard (USCG) is charged with maintaining an acceptable level of safety in US ports and waterways. Allocating resources to solve safety problems is difficult because multiple attributes of a port or waterway affect its safety and determine whether a particular safety measure will improve it. We based the ports and waterways safety assessment (PAWSA) model on multiattribute decision analysis techniques and local experts' and stakeholders' assessments of safety levels and the effects safety alternatives would have on these levels. The USCG used the PAWSA model to justify funding for four new vessel traffic service centers and to determine new technology requirements for all commercial vessels using US waters. The USCG has adopted it as a permanent part of its safety management tool kit.

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During the early 1990s, the United States Coast Guard (USCG) invested in a project called VTS 2000. A vessel traffic service (VTS) is a traffic control center for ships using a particular port or waterway, similar to an air traffic control center. The USCG analyzed risk factors for 23 ports and determined that seven of them needed a VTS to reduce risk to an acceptable level. However, because the public had no role in the assessment process, people did not trust the results, and the politicians killed the project in the budgeting process. In the end, the USCG cancelled seven contracts for the new VTS.

In the 1997 Department of Transportation Appropriations Act, Congress directed the USCG "to identify minimum user requirements for new VTS systems in consultation with local officials, waterways users, and port authorities" and to review opportunities for private and public partnerships in VTS operations. The USCG asked maritime and port community stakeholders to identify the needs of waterway users with respect to ensuring the navigational safety in US ports and waterways. It formed a group to discuss such needs, whose members were drawn from the American Association of Port Authorities, the American Pilots' Association, the American Waterways Operators, the Council of American Master Mariners, Intertanko, the Passenger Vessel Association, the Natural Resources Defense Council, the US Chamber of Shipping, and the USCG.

Under the auspices of the Marine Board of the National Research Council, the group held four meetings between January and March 1997. The group conducted the national dialog to provide the foundation for developing an approach to the VTS that would meet the shared government, industry, and public objective of ensuring the safety of vessel traffic in US ports and waterways in a technologically sound and cost-effective way (USCG 2001). The participants agreed that the USCG and port users and stakeholders should take part in determining whether a VTS was needed in a particular port. Such collaborative analysis improves the decision-making process and increases the chances of implementing study recommendations (Busenberg 1999, 2000; Charnley 2000). Furthermore, the USCG should use defined criteria to conduct an initial screening and identify ports that might be candidates for a VTS. Each port's users and stakeholders should consider these criteria in detail and determine whether the port needs a VTS.

The vessel traffic management (VTM) technologies the national dialog group's participants endorsed were automatic identification systems (AISs) employing differential global positioning systems (DGPSs) and on-board transponders. A vessel's AIS emits its exact position from the DGPS. On-board equipment picks up the signals from all nearby, similarly equipped vessels and maps their positions, courses, headings, speeds, and identifiers. Augmented systems also provide weather forecasts, data on currents, and depth and emergency information. These enhanced automatic identification systems (EAIS) are full information systems for port users that do not depend on an on-shore facility with 24-hour staffing. The next level of VTM implementation is a vessel traffic information system (VTIS), which includes a person on watch who provides further information to vessels and warns them of high-risk situations or errors. USCG or industry-sponsored personnel can staff VTISs. The highest level VTSs, such as those in Prince William Sound (Alaska), Seattle, and New York, are staffed by a captain of the port with authority to order vessels to follow instructions in situations of extreme risk.

Maritime Risk Assessment

In January 1997, the USCG released its initial "Risk-Based Decision-Making Guidelines." Risk-based decision making is a "process that organizes information about the possibility for one or more unwanted outcomes into a broad, orderly structure that helps decision makers make more informed management choices" (USCG 2003, p. 1). The guidelines cover the standard quantitative risk assessment (QRA) tools used to study nuclear power and chemical production plants (Bedford and Cooke 2001), namely, failure mode and effect analysis, fault trees, event trees, and hazard and operability analysis, that have been used to analyze maritime static systems, such as offshore oil and gas platforms (Pate-Cornell 1990), but have proved of little use for analyzing entire port systems (Fowler and Sorgard 2000).

We have assessed risk in several ports: Prince William Sound's oil-transportation system (Merrick et al. 2000, 2002), Washington State's ferry system (Grabowski et al. 2000, van Dorp et al. 2001), and San Francisco Bay's ferry system (Merrick et al. 2003). We used simulation to model the dynamic nature of each port system, combining simulation models with standard risk-assessment methods. The simulation models often identified trade-offs between targeting safety concerns with specific interventions and the migration of risk to other parts of the system (Merrick et al. 2000). Although these large-scale studies successfully assessed safety-intervention measures, identified safety trade-offs, and built stakeholder trust (Merrick et al. 2002), their cost and duration put such studies beyond the USCG's reach. It must consider many ports, inland waterways, and lakes. The USCG needs a tool to assist it in making decisions based on the trade-offs between targeting specific safety concerns and maximizing the overall level of safety in US ports and waterways.

The USCG performed two studies aimed at producing such a tool, its "Analysis of Ports' Needs" (USCG 1973) and its "Deployment Requirements for U.S. Coast Guard Pollution Response Equipment" (Maio et al. 1991). In both studies, the analysts applied multiple regression to nationwide accident data. They omitted many factors that affect risk because of lack of data, particularly data on human error in maritime operations, and thus their results were of limited utility (Harrald et al. 1992).

Making Decisions About Safety

To restart the decision process for allocating VTM technology after the failure of VTS 2000, the USCG sought a method of assessing risk in ports and waterways and identifying which ports needed new VTM technology. It also wanted to reduce the cost of assessing risk. We developed the ports and waterways safety assessment (PAWSA) model based on our experience in the Prince William Sound risk assessment (Harrald et al. 1998; Merrick et al. 2000, 2002) and in light of the dialog group's findings on the attributes of ports or waterways that affect safety.

At first, USCG personnel considered simply gathering data on these attributes for ports and waterways in the hope of determining which performed poorly on many attributes and thus identifying high-risk systems. However, this procedure did not produce useful answers. For example, although Prince William Sound is a very challenging environment in which to

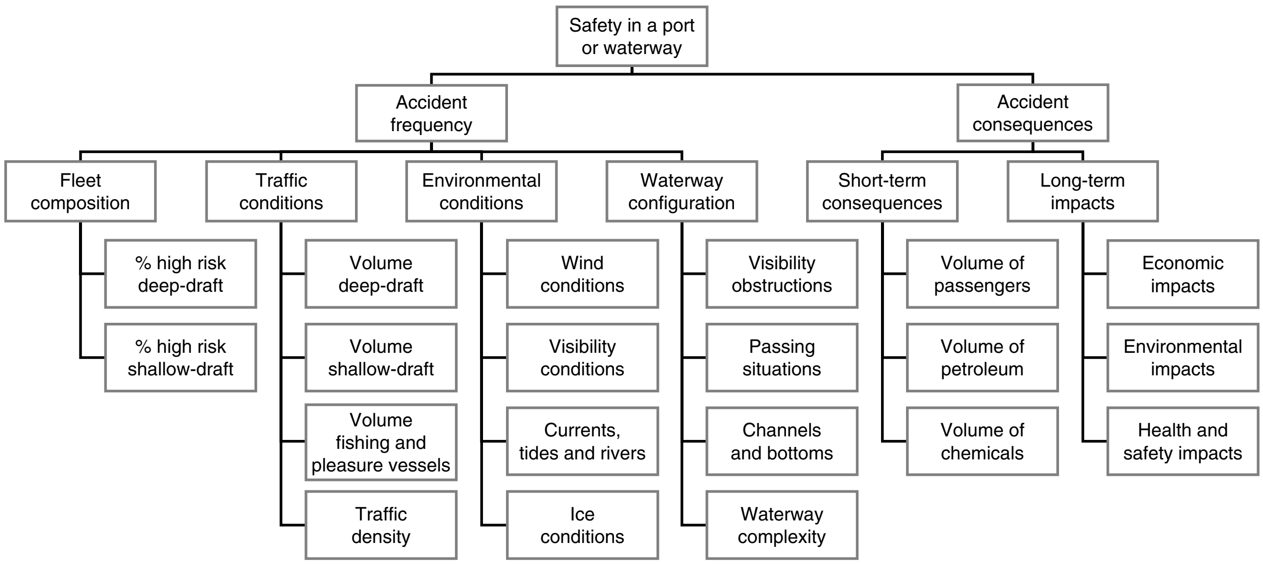

Figure 1: The PAWSA model is a hierarchy of the port or waterway's attributes that affect its safety. These attributes were defined by the national dialog group on port safety convened by the National Research Council.

sail (icebergs, high winds, and fog) and in which the consequences could be catastrophic (high volumes of oil transported and environmentally sensitive populations of wildlife), it has a fairly low level of traffic and the ships are owned by organizations with good safety records.

In building our multiple-attribute decision model, we evaluated the factors that should be considered in making a decision and then combined the factors into a tree-like hierarchy (Figure 1). Developing multiple-attribute models for risk assessment can be difficult because experts can have difficulty determining the parameters (Davidson 1997, Davidson and Lambert 2001). Yet, such a model is useful to decision makers who would otherwise make such comparative judgments informally. When humans want to achieve multiple objectives, they often rely on a heuristic called *satisficing* (Simon 1979), picking their most important objective and choosing the alternative most likely to achieve that one objective. If multiple alternatives are equally likely to achieve this objective, they turn to the second most important and so on. We can see such a process in most industries, where organizations consider mainly economic objectives in planning and making decisions. They then consider safety in terms of meeting government regulations while maintaining profitability.

We can define *risk* as a measure of the probability of an unwanted event and its impacts or consequences (Lowrance 1976). The attributes that make up risk are, therefore, those that affect the accident probability and the impacts or consequences of potential accidents. We combined the attributes determined by the national dialog group into a tree-like hierarchy (Figure 1) with six main groups; four of these groups affect accident frequency, and the other two affect the consequences of potential accidents, each of which must be minimized to achieve the overall objective of maximizing safety in a given port or waterway.

We held two sessions with panels of experts to test the multiple-attribute decision-analysis approach. Harrald had used using the analytic hierarchy process (AHP; Saaty 1980) on several projects; we used AHP and the Expert Choice software package for the proof-of-concept sessions with experts. We ran the first session at George Washington University's management decision center in Ashburn, Virginia, on July 6, 1998. We chose the experts based on their broad experience with multiple ports, gathering 15 experienced mariners: eight licensed merchant mariners and seven Coast Guard officers, all with experience in a wide range of US ports and vessel types. We conducted the second session at the marine safety office in Hampton Roads, Virginia, on November 19, 1998. We chose the experts based on their affiliations with organizations involved with the port of Hampton Roads: the Virginia Pilot's Association (2), the Hampton Roads Maritime Association (1), Naval Station Norfolk Pilots (1), Naval Station Norfolk Port Operations (1), McAllister Towing (1), National Oceanographic and Atmospheric Administration (1), USCG Auxiliary (1), Norfolk Shipyards Terminal (1), the US Army Corps of Engineers (2), and USCG Marine Safety Office Hampton Roads (1).

The results of the two sessions were promising: The experts largely agreed on the assessments. We could rely on the model to assess the port risk based on the panel members' expert knowledge. Furthermore, we could easily trace the model's results back to the expert inputs. However, both the model and the elicitation process needed improvement if they were to be used as a decision-making tool (Harrald and Merrick 2000).

The PAWSA Model

The PAWSA model is a linear combination of the attributes, like a linear-additive value function (Keeney and Raiffa 1993, ch. 3; Kirkwood 1997, ch. 4). If we denote n factors that should be considered in the decision and denote the level of the attributes for a particular port with a particular technology by $x_1, \ldots, x_n$, then we can write the linear-additive value function as

$$v(x_1, \ldots, x_n) = w_1 v_1(x_1) + \cdots + w_n v_n(x_n),$$

where $v(x_1, \ldots, x_n)$ is a value or preference function that allows us to rank alternatives, the $v(x_i)$ are single-dimensional value functions that essentially convert each attribute x_i to a common scale, and the w_i reflect the importance of each attribute x_i to overall preference over the range of alternatives considered. The x_i are then objective attributes that should be measured on either constructed or natural scales. However, we calculate the weights w_i and single-dimensional value functions $v(x_i)$ from the experts' subjective ratings. Although we now support the use of multiple-attribute value or utility functions over AHP for theoretical reasons (Dyer 1990, Saaty 1990, Harker and Vargas 1990), as a legacy of our use of AHP in the proof-of-concept phase, the USCG retained the form of questions placed to the experts and the calculation technique used to find the w_i and $v(x_i)$ from AHP.

For each attribute, we elicited weights from the expert group. We chose example best-case and worst-case ports based on interviews with Coast Guard marine safety staff and historical data (Table 1), and we used these ports to create fictitious ports, Port Heaven and Port Hell. For Port Hell, we set all attributes at the levels of the worst-case ports, and for Port Heaven, the best-case ports. We asked experts to compare attributes in pairs. For instance, in the first comparison, they compared fleet composition and traffic conditions. We asked them to imagine Port Hell and then change one criterion to a best-case level taken from Port Heaven. We asked them which criterion they would most like to improve to the best-case level and by how much.

In this manner (similar to Kirkwood 1997, pp. 68–70, swing weight approach), we put the experts in a risk-reduction state of mind. However, we gathered their actual responses on AHP's 1 to 9 scale (Saaty 1980). In this scale, a 1 indicates that improving both attributes from their worst-case level to their base-case level is equally important, whereas a 9 toward one factor indicates that improving that factor is "significantly more important" than improving the other (Table 2).

To encourage discussion and elicit the weights in the PAWSA sessions, the consultants facilitating the sessions used the following scheme. They asked the experts to publicly announce their first responses to each question and displayed the experts' actual values, allowing the group to discuss the differences between the members' opinions and experience. The experts then modified their responses if they wanted to and wrote down their final responses and submitted them privately. The consultant's goal was to encourage discussion but also to allow the experts to provide their honest responses unaffected by group pressure. The USCG then calculated the weights for each expert and averaged them using a simple arithmetic average across the experts. They repeated this process for all levels of the tree, with a booklet of questionnaires for each level of assessment, to obtain the weights w_i.

For some of the attributes x_i in the model, we constructed evaluation measures because no natural scales were available. For example, the national dialog group defined four levels of exposure to hazardous wind conditions:

NDG attributes	Measurement scale	Ports with less safe scores for this attribute	Ports with safer scores for this attribute
Fleet composition	Proportion of vessels operated by poor organizational performers	Lower Mississippi Houston/ Galveston	San Diego Valdez/PWS
Traffic conditions	Volume and density of traffic	Lower Mississippi Houston/Galveston Mouth of Ohio River	Valdez/PWS Fort Lauderdale/Port Everglade
Wind conditions	Severity of winds, frequency of poor visibility, strength of currents, presence of icebergs	Anchorage Valdez/PWS St. Mary's River	San Diego Los Angeles/Long Beach Hampton Roads
Waterway complexity	Blind turns or intersections, difficult meetings and overtaking	New York Harbor Berwick Bay San Francisco Mouth of Ohio River	Fort Lauderdale/Port Everglade Los Angeles/Long Beach
Potential consequences	Nos. of passengers, volumes of petroleum and other hazardous cargoes	New York Harbor Houston/Galveston Valdez/PWS	Columbia River Wilmington St. Mary's River
Potential impacts	Human population dependent on port operation, environmentally sensitive area	San Francisco Valdez/PWS Puget Sound New York Harbor	St. Mary's River Port Canaveral

Table 1: The national dialog group defined the attributes of a port that affect safety. We defined the measurement scale on which these attributes could be assessed and ports that represented examples of the best and the worst performing ports around the United States for each attribute.

Level 1: On average, fewer than two days per month of winds over 20 knots,

Level 2: Fewer than five days a month of winds over 20 knots,

Level 3: More than five days a month of winds over 20 knots but anticipated,

Level 4: More than five days a month of winds over 20 knots without warning.

The group defined the scale carefully so that a mariner could specify his or her experience with wind exposure in a given port. For other attributes, we developed natural evaluation measures. However, for the proof-of-concept sessions, the data for the relevant ports were not yet available. Thus, in these early sessions, we relied on poorly defined evaluation measures, asking for a subjective ranking from 1 to 9 of a port's traffic volume or the calling fleet's organizational performance. These ratings were supposed to be used only in the proof-of-concept session and were to be replaced later by the natural measurement scales or, at worst, proxy scales. We would then elicit single-dimensional value functions from the experts as we had with the constructed scales. Unfortunately, the USCG decided not to do this, and in the final model, some attributes still had subjective ratings.

With the attributes in place, we developed the single-dimensional value functions $v(x_i)$ by comparing the levels of the constructed measurement scales using AHP comparisons; we then scaled the AHP weights obtained from 0 (for the lowest risk level) to 100 (for the highest risk level; Table 3). Using the AHP calculation method, we obtained weights from these ratings and then normalized the weights to the range 0 to 100 to find a single-dimension value function.

To facilitate implementation, the Volpe National Transportation Systems Center, under contract to the USCG, created an Access database tool and a set of questionnaire booklets for the experts to fill out. The facilitators entered the results into the database using simple forms, thus quickly feeding the results back to the panel. USCG personnel and outside contractors from Potomac Management Group, Inc., facilitated the sessions. Once the experts answered all the questions, the tool took the attribute levels, the single-dimensional value functions, and the weights and use the linear-additive form in the equation to arrive at a risk score for the port.

The USCG wanted to use the PAWSA process to elicit information about safety from port users and stakeholders and to prompt discussion. Once the

Question	Left attribute	L	R	Right attribute
1	Fleet composition	8	0	Traffic conditions
2	Fleet composition	8	0	Environmental conditions
3	Fleet composition	8	0	Waterway configuration
4	Fleet composition	8	0	Short-term consequences
5	Fleet composition	8	0	Long-term impacts
6	Traffic conditions	0	5	Environmental conditions
7	Traffic conditions	3	0	Waterway complexity
8	Traffic conditions	5	0	Short-term consequences
9	Traffic conditions	4	0	Long-term impacts
10	Environmental conditions	5	0	Waterway configuration
11	Environmental conditions	3	0	Short-term consequences
12	Environmental conditions	2	0	Long-term impacts
13	Waterway configuration	2	0	Short-term consequences
14	Waterway configuration	0	2	Long-term impacts
15	Short-term consequences	0	3	Long-term impacts

Table 2: We elicited the weights by comparing swings in the attributes two at a time and provide an example here. The assessors of the ratings in the table would consider the change in risk from the swing in the fleet composition from a port like the Lower Mississipi to that in a port like San Diego as more important than the swing in any of the other five groups of attributes, as they entered a rating of 8 on the side of fleet composition in the first five comparisons. When we calculate the weights using the AHP calculation process, we obtain the following: fleet composition 53.6%, traffic conditions 13.3%, environmental conditions 17.2%, waterway configuration 4.9%, short-term consequences 3.6%, and long-term impacts 7.4%.

model defined the attributes of a safe port, port users and experts in navigating the waterway discussed safety under a common framework using common language. For each session, we asked the USCG captain of the port to convene a panel of local experts and stakeholders. A port-risk-assessment officer coordinated activities before, during, and after the safety workshop. The criteria for membership on a panel included regular use of professional skills in pilotage, ship handling, aids to navigation, maritime-law enforcement, vessel traffic management, navigation, protection of natural resources, and knowledge of port economics that could influence or be affected by vessel casualties (USCG 2001). The USCG decided that each port would develop its own PAWSA model with its own set of weights and single-dimensional value functions. The responsibility for using the results of a PAWSA session lies with the local port authorities and their federal representatives in Congress, rather than the USCG.

(The USCG Web site, http://www.navcen.uscg.gov/mwv/projects/pawsa/PAWSA_Back.htm refers to the method used as AHP without differentiating it from the modified method we implemented.)

Question	Left attribute level	Rating	Right attribute level
1	On average, fewer than two days a month of winds > 20 knots	4	Fewer than five days a month of winds > 20 knots
2	Fewer than five days a month of winds > 20 knots	5	More than five days a month of winds > 20 knots but anticipated
3	More than five days a month of winds > 20 knots but anticipated	7	More than five days a month of winds > 20 knots without warning

Table 3: The single-dimensional value functions were also calculated using pairwise comparisons of the levels of the constructed attributes. This table shows a possible set of ratings. (Risk will increase the more severe the wind conditions, thus all value functions are strictly increasing, and we do not need to allow the expert to assign values to the left or right attribute as we did in Table 2.) We obtain the following weights from AHP: Level 1 = 5.7, Level 2 = 13.2, Level 3 = 29.3, and Level 4 = 51.7. We then normalize the values to the range 0 to 100 by subtracting the lowest weight from each and dividing by the range between the lowest and highest weights to obtain the following values for $v(x_i)$: Level 1 = 0, Level 2 = 16.25, Level 3 = 51.25, and Level 4 = 100. Again, we average the values for any given level of each $v(x_i)$ across the experts using a simple arithmetic average.

Problems with PAWSA

The model implemented in PAWSA had problems: (1) the use of AHP (Dyer 1990), (2) possible inappropriateness of the linear-additive form, and (3) the lack of comparability across ports.

Many authors have criticized the AHP from both practical and theoretical perspectives (Dyer 1990). The chief practical consideration is that AHP elicitation questions are difficult to answer because they have no reference point and do not consider the range in the variation of the attributes. We alleviated this problem by using Port Heaven and Port Hell in eliciting weights. The main theoretical criticism is that adding an alternative to some ranked list of alternatives can cause reversals in the rankings (Belton and Gear 1983, Dyer and Wendell 1985), making the rankings somewhat arbitrary. However, because we use the AHP to obtain weights and value functions for a fixed number of attributes and levels, we will not have this problem. Our main criticism of the AHP is the lack of objective data in forming the rankings. We avoided this problem by introducing (mostly) constructed evaluation measures for the attributes. The weights and single-dimensional value functions were, however, still subjective.

Regarding the appropriateness of the linear-additive model, we were thinking more of risk in determining the factors in the PAWSA model than of making a decision; the factors are similar to those used in the probabilistic risk-assessment model in the Prince William Sound risk assessment (Merrick et al. 2000). Multiple-attribute decision models (Kirkwood 1997, Keeney and Raiffa 1993) should be based on the factors that should be considered in making a decision. The factors are turned into objectives, indicating the direction of improvement. Analysts assess whether they are end (fundamental) objectives or just means to ends (Keeney 1992). They use the fundamental objectives to form the model. They then establish evaluation measures, or attributes, to measure the levels of the fundamental objectives and insert them in the hierarchy. According to preference theory, in a linear combination of attributes, the attributes should be preferentially independent (we did not consider uncertainty in the attributes in the PAWSA process). This requires that our preferences concerning each subset of the attributes should not depend on the levels of attributes outside that subset. Because we did not create the PAWSA model by considering means-ends relationships and forming a hierarchy of fundamental objectives, we can construct counterexamples to the preferential independence requirement.

For example, if there is no traffic in a port or waterway, then the environmental and waterway conditions do not affect safety; if we have a large volume of traffic, we prefer good environmental and waterway conditions. In another example, we have two ports, one approached by a narrow channel bordered by rocks with no high winds, and the other approached by a wide, deep channel with occasional high winds. Fishing and pleasure vessels would have no problem navigating the first port but would have problems with the wind in the second port. Large, deep-draft vessels would have no problem with the wind in the second port but would have problems with the narrow channel in the first port. These two examples imply preferential dependency between some subsets of the attributes, which could make the use of a linear combination of the attributes invalid. However, the USCG uses the PAWSA model for traffic levels ranging from the highest to the lowest levels seen in the candidate ports and waterways. The ports considered must have significant volumes of deep-draft traffic and shallow-draft fishing and pleasure traffic. The USCG is not considering reductions in the levels of any type of traffic. Thus, the preferential dependency is slight in the range of the attribute space that the model must reflect. The linear-additive value model is generally accepted as robust (Belton 1985, Edwards 1978), so although it is not completely valid, we can consider a linear-additive combination of the attributes a first-order approximation to the true preference structure.

A final problem with the PAWSA model remains from the proof-of-concept sessions: the ports are not truly comparable. Experts providing subjective assessments for some attributes on a 1 to 9 scale may use the scale differently. Such scales do not pass the clarity test (Howard 2004), that is, a clairvoyant with perfect knowledge of past and future states should be able to define the level on the scale without ambiguity. It would be preferable to use natural measurement scales for these attributes and a value function to map them to a common value scale as in multiple-attribute value functions (Keeney and Raiffa 1993, Kirkwood 1997), as we do with the constructed scales. Furthermore, each port had its own set of weights and single-dimensional value functions. To allow comparisons across ports, we would have to aggregate these weights and functions to create one PAWSA model through which we would feed each port's attributes to find its risk score.

The lack of comparability across ports also makes validating the model difficult. Because of the potential theoretical problems with the model, it is important to validate the results. However, risk assessments typically deal with low-probability, high-consequence events, making statistical validation of their results difficult, even with nationwide data (Merrick et al. 2002). Because the ports are essentially measured on different scales, it is impossible to analyze the correlation between historical accident frequencies and the PAWSA score, a typical form of validation. Although participants in the sessions found that the safety problems the PAWSA models displayed for ports were reasonable and in line with their experiences, the results of PAWSA have been statistically validated.

Despite these problems, the USCG held PAWSA sessions in 26 US ports and waterways (Figure 2). In each session, the experts determined weights and single-dimensional value functions for each attribute and the

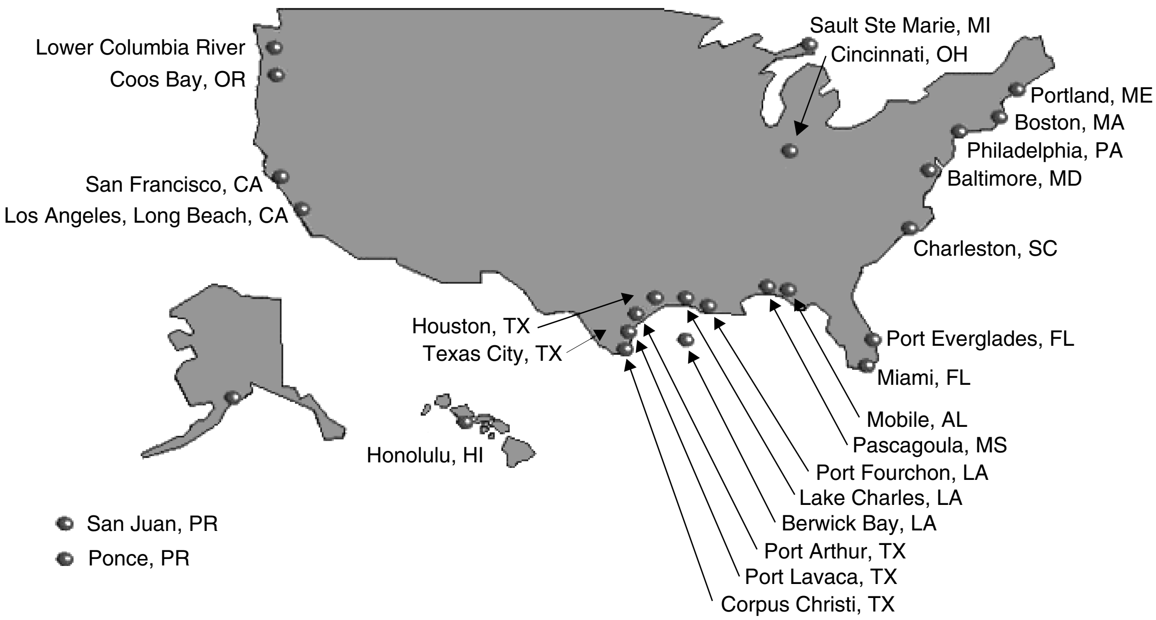

Figure 2: PAWSA sessions were initially held in 26 ports and waterways around the United States.

levels of the attribute at that port. In all, 340 experts and stakeholders participated in PAWSA sessions.

Analyzing Port Vulnerabilities

To determine why a port is vulnerable to accidents, we compared it to the fictitious Port Heaven. A Coast Guard team facilitated a PAWSA session for the Lake Charles port area on April 25 and 26, 2000. For the workshop, the Coast Guard captain of the port brought together 24 experts and stakeholders to represent a cross-section of waterway users.

We calculated the scores under the six main groups of attributes (Figure 1) for Lake Charles and Port Heaven and then calculated the gaps between Lake Charles and Port Heaven. The gaps indicate room for safety improvements (Figure 3). Fleet composition has the largest gap among the four main groups of attributes that affect accident frequency. However, the safety gaps for short-term consequences and long-term impacts are both larger still. We broke down the safety gaps one more level and ranked them (Table 4), which revealed that the safety gaps for Lake Charles are driven by concerns about the volume of passengers, petroleum and other chemicals, health, safety, the economic and environmental impacts of accidents, traffic density, complexity of the waterway configuration, and organizational performance of the deep-draft and shallow-draft fleets using the waterway. The city of Lake Charles is a center for large chemical, petroleum, and natural gas industries. Furthermore, the area includes wildlife refuges, oyster beds at the lower end of Calcasieu Lake, and breeding grounds for endangered species. The experts believed that, although responsible, successful companies operate most of the cargo and tank vessels using the port, 20 to 30 percent of deep-draft vessels fall into the high-risk category because crews lack competency and the ships are in poor condition. Furthermore, whereas the shallow-draft tugs, ferries, and charter fishing boats operating in the river are generally well maintained and professionally operated, the transient tugs using the waterway tend to be poorly maintained and operated by less-experienced personnel.

Assessing Technology Effectiveness

In the next step in the PAWSA process, we extended the results of these sessions to determine the effectiveness of the various VTM technologies. The consultant who facilitated the sessions developed a method to consider VTM technologies that is inconsistent with the usual approach for making decisions with multiple-attribute value functions, which caused problems. At the end of sessions, the participants decided whether each attribute's risk contribution (in

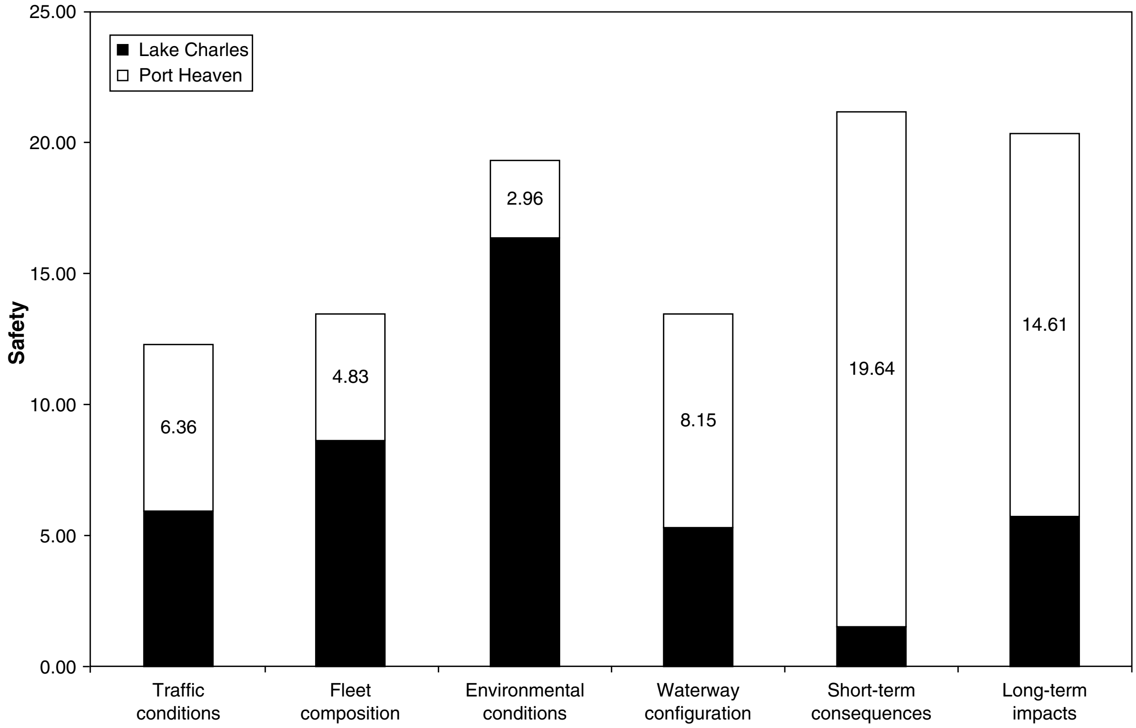

Figure 3: A PAWSA model, such as the one created for Lake Charles, can be used to compare the port to a theoretical perfect port (Port Heaven) under any attribute or group of attributes. The black bar in this figure shows the score obtained by Lake Charles for the six main groupings of attributes, and the white bar shows the difference between Lake Charles and Port Heaven.

Attribute	Safety gap
Volume of chemicals	8.89
Health and safety impacts	7.49
Volume of passengers	6.94
Waterway complexity	4.89
Environmental impacts	3.86
Volume of petroleum	3.81
Economic impacts	3.25
Traffic density	2.89
Percentage high-risk shallow-draft vessels	2.42
Percentage high-risk deep-draft vessels	2.41
Passing situations	1.65
Volume of fishing and pleasure vessels	1.41
Volume of shallow-draft vessels	1.29
Ice conditions	1.18
Wind conditions	1.00
Channels and bottoms	0.92
Hazardous currents and tides	0.77
Volume of deep-draft vessels	0.77
Visibility obstructions	0.69
Visibility conditions	0.00

Table 4: Using a PAWSA model, we can rank safety problems in the port by calculating the safety gaps, the difference between the port's score and that of Port Heaven under each attribute.

the form of the safety gap) was acceptable. If not, the experts decided which VTM technology would reduce the port's risk to an acceptable level. They thus obtained a picture of which technologies to use to solve the different problems in the port or waterway.

At Lake Charles, a major concern was the organizational performance of the vessels using its waters. Most VTM technologies do not address this problem, but a VTIS and VTS can provide oversight and capture errors, stopping problems before they lead to accidents. A VTS would be slightly more effective than a VTIS because the captain of the port can act if a vessel ignores suggestions. Although no VTM technology reduces traffic levels, the information they provide helps vessels to plan their routes and departure times and to cope with the complexity of the waterway and thus slightly reduce traffic density.

In terms of environmental conditions, AIS, EAIS, VTIS, and VTS can help vessels to handle hazardous visibility conditions (fog), sight-line obstructions, and complex passing and meeting situations. VTM technology cannot change the short-term consequences of an accident, but a VTIS and a VTS can help those managing rescue and recovery efforts, slightly improving the long-term effects.

The results of the process designed by the consultant who facilitated the sessions are qualitative, not quantitative. The USCG used the results of several early PAWSA sessions to build a sense of which VTM technology solutions were generally appropriate for ports with low scores in particular attributes. It did not determine the effects implementing the VTM technology had on the attributes, however. In Lake Charles, an AIS would reduce the risks from poor visibility and waterway complexity, but a VTS or VTIS would be needed to reduce traffic density, organizational problems, and the short- and long-term consequences of accidents.

One main problem with the consultant's approach is that we cannot aggregate the results. The model does not provide prescriptive recommendations of actions to take. The decision makers gain an understanding of different VTM solutions and their appropriateness but not a final answer. Using the assessments made in a PAWSA session, the port stakeholders follow the usual budgetary procedures to obtain funding. In the case of Lake Charles, Congress decided that the benefits a VTS provided beyond those of a VTIS were not great enough to warrant the federal expenditure. Local stakeholders performed no sensitivity analysis on the results of the model.

A National Model

We developed an aggregated national model based on the assessments from the 26 sessions. We aggregated the weights and the single-dimension value functions for the constructed scales and proposed natural (and a few proxy) measurement scales for the remaining attributes. With the national model, we could compare the safety problems and the effect of VTM technology in different ports. Furthermore, we could simplify the PAWSA sessions to a discussion of the effect of VTM technologies on the objective measurement scales. The usual method of making decisions with multiple-attribute value functions is to assess the changes in each attribute level $x_1, \ldots, x_n$ caused by each alternative and then calculate aggregated scores for each alternative using the value function $v(x_1, \ldots, x_n)$. The resulting prescriptive recommendations indicate what the VTM alternative is most appropriate for a given port or waterway and the relative value of the alternatives.

In our proof-of-concept sessions, experts found it difficult to assess the impact of alternatives on the attributes, for example, the impact of a VTS on visibility problems. The VTS does not change the number of foggy days per year. We included the attribute "visibility conditions" in the model because the underlying safety objective is to minimize the vessels' exposure to hazardous visibility conditions, and this attribute measures the attainment of that objective. Clearly, a VTS can provide forecasts, suggestions on avoiding hazardous visibility conditions, and information about the locations of other vessels and obstructions, thus reducing the impact of, say, fog on the level of safety in the port or waterway.

We asked a small group of maritime experts to assess the effect of each VTM alternative on each attribute. We then calculated the risk scores for the VTM alternatives using the weights and single-dimensional value functions from the national model, that is, from the aggregation of 26 PAWSA sessions (Figure 4). Lake Charles could improve safety somewhat by optimizing the current system and AIS technologies. With VTIS or VTS, it could make significant improvements in safety (Figure 4). Also, with an assessment of a port or waterway based on the national model, we could perform sensitivity analysis on the effect of parameter values on model recommendations.

Despite the apparent improvement in the process and the results with this aggregated model, the USCG decided to stay with the local port models. It based this decision on sound risk-analysis principles. The USCG was very interested in ensuring that analyses followed a collaborative process and that it minimized the appearance of federal oversight. We had just completed the Prince William Sound risk assessment, and the stakeholders had implemented all recommendations because they trusted the analysis. In fact, researchers studied the Prince William Sound risk assessment as an examplary collaborative process (Busenburg 1999, 2000; Charnley 2000). The USCG, which collaborated in the assessment, wished to ensure similar success for PAWSA with successful implementation of the resulting recommendations. It

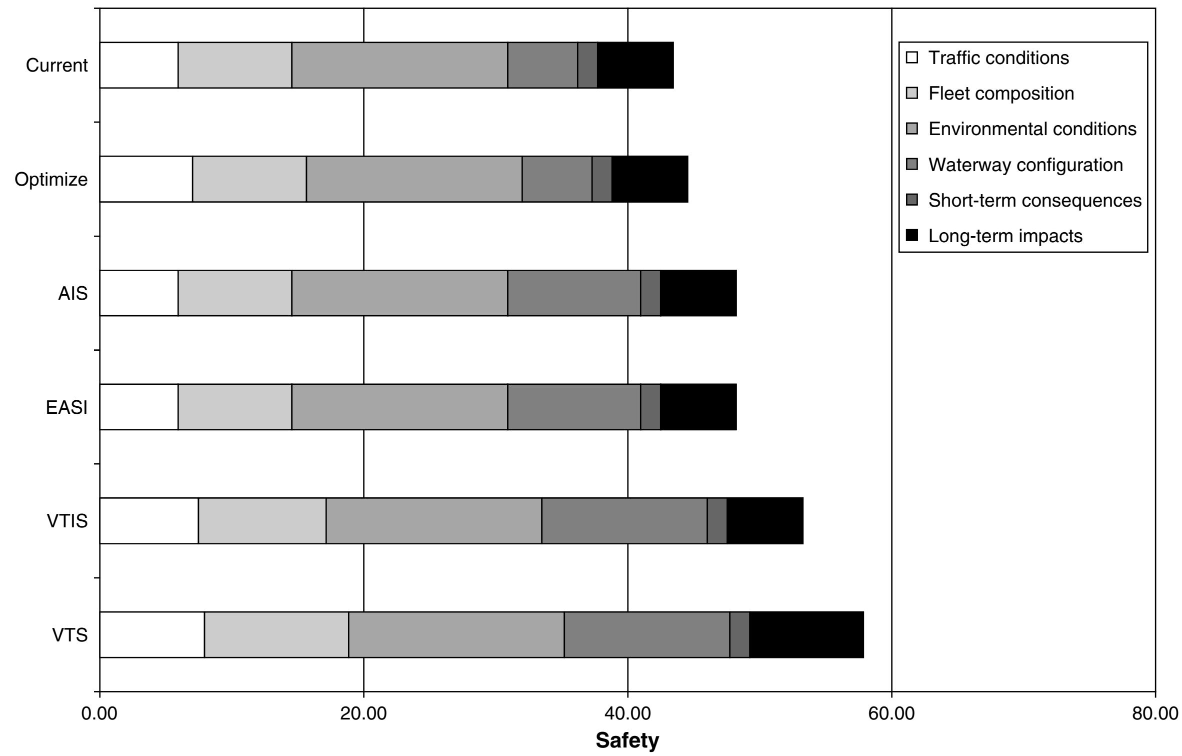

Figure 4: The aggregated national model would have been capable of assessing the impact of each given VTM technology on safety in a given port and comparing this effect across ports. To demonstrate this approach, we created an assessment of the effect of VTM technology on Lake Charles by having a small group of experts assess the changes caused in each attribute by each VTM technology and then recalculating the scores for each one.

saw the absence of federal "tampering" as a key to success and wanted local port stakeholders to feel that they owned the results and recommendations. USCG personnel or their consultants combining the local assessments into a national model could alter this perception. Thus, the model remained fully locally determined, and the local port stakeholders were responsible for using the results to lobby for federal resources. This is an interesting example of a situation in which the academically obvious next step is not necessarily practical.

Conclusions

Local stakeholders use the PAWSA model and process to decide what vessel traffic management system to adopt in a traceable, coherent manner based on effective risk-management methods. The approach has not been limited by available data because the USCG obtains expert judgments during the PAWSA sessions. PAWSA is now a part of the safety decision processes within the USCG and a tool that individual ports and waterways use in managing their own safety. The USCG is developing a new version of PAWSA, revising the attributes based on suggestions made at PAWSA sessions, which should reduce preferential dependency. The new version will include constructed scales for all attributes and single-dimensional value functions. Constructed scales are not optimal because they limit the granularity of the model to the number of discrete levels in the constructed scales. However, the USCG did not have a data-collection process in place that would allow it to use our suggested natural measurement scales, and constructive scales will replace the subjective ratings for these attributes.

The new version of PAWSA can only build on the success of its predecessor. The PAWSA sessions have supported the implementation of two nationwide safety improvements: requirements that all commercial vessels carry AIS and DGPS systems. Funding has also been earmarked for a new vessel-traffic-service center in Port Arthur, Texas, projected to cost $10.5 million for its construction. Port stakeholders in Charleston, South Carolina, Corpus Christi, Texas, and Tampa, Florida, have decided to fund privately operated VTISs, with Corpus Christi estimating the cost of upgrading its harbor operations center to be $3.6 million. The other two ports require construction from scratch and are seeking proposals. The results of PAWSA sessions in Lake Charles, Louisiana, and Pascagoula, Mississippi, have shown insufficient need for a VTS, despite strong local support. Lake Charles has sought a further PAWSA session to assess the effects of a new liquid natural gas terminal.

The process has produced side benefits; The Army Corps of Engineers has used the results to justify budgets for dredging projects in Tampa, Florida, and for improving communication systems in Cincinnati, Ohio. PAWSA participants in Valdez, Alaska, realized that the increasing rate of glacial melting was increasing the number of icebergs that oil tankers encountered in traffic lanes. They decided to implement a new radar technology to track the icebergs.

However, the PAWSA process has had a more pervasive effect on the maritime industry. The approach is less costly than previous approaches and the technique easier than previous techniques. USCG personnel perform much of the work, not expensive consultants or academics. Stakeholders and local experts are responsible for the inputs that drive the model. Such collaborative analyses increase people's trust in the results and improve the chances of implementation (Charnley 2000, Slovic 1993). PAWSA is a significant application of multiattribute decision analysis in the federal domain that shows promise for use in many safety-based decisions in ports and waterways around the United States.

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J. M. Sollosi, Chief, Office of Vessel Traffic Management, US Coast Guard, 2100 Second Street, S.W., Washington, DC 20593-0001, writes: "This letter is to inform you of the success the U.S. Coast Guard has had in our Ports and Waterways Safety Assessment (PAWSA) program. At the core of this program is a process that was developed for us by a team that included Dr. Jason Merrick of Virginia Commonwealth University and Dr. Jack Harrald of the George Washington University.

"PAWSA is a systematic risk assessment process to evaluate navigation safety conditions in ports and waterways and determine if additional or alternative risk mitigation measures are necessary. It provides a structure for identifying risk drivers and evaluating various mitigation measures through input from waterway users. The process has been applied 37 times around the country. The results have been used in developing regulations, making investment decisions, seeking legislative support and allocating resources.

"PAWSA results supported the implementation of a significant nationwide safety improvement: the mandatory carriage of Automatic Identification Systems and Differential Global Positioning Systems on all commercial vessels. PAWSA results were instrumental in obtaining Congressional support and funding for new Vessel Traffic Service (VTS) centers in Port Arthur, Charleston, Corpus Christi and Tampa. The total investment in these projects will exceed $20 million. The costs will be a mix of federal and private sector investment. The PAWSA process has also demonstrated that a VTS is *not* the proper tool to address the navigation risk in some ports, in spite of local support for such systems.

"Other benefits of the process include justification for dredging projects, communications systems improvements in Cincinnati, and legislation in Massachusetts for oil spill response. Through the Valdez PAWSA, it became apparent that current practice was not sufficient to deal with the number of icebergs oil tankers encountered in the traffic lanes, and we were able to gain support for new radar technology to track ice. Less readily measurable, but equally important, are the improved lines of communication and cooperation between stakeholders that PAWSA produces.

"Like all good tools, PAWSA has also been misapplied. We have been called in to use the process to settle a rare dispute between pilots and the port and to support preconceived conclusions. In all cases, the validity of PAWSA was upheld, and we were able to use the structured process to properly refocus the discussion on navigation risk.

"Lastly, the process has been recently recognized internationally. In May 2004, the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) adopted PAWSA as part of its Port Risk Model. The government of Australia applied the process in assessing various protective measures for the Torres Strait and Great Barrier Reef. Their results were presented to the International Maritime Organization Sub-Committee on Safety of Navigation. International PAWSA experience will increase beginning with a training seminar in Copenhagen in June 2005.

"PAWSA has proven to be a dependable tool. The results it produces are accepted by the people that have participated in the process, and decisions made based on PAWSA results are defensible. The Coast Guard and the maritime community look forward to its continued use."