CHAPTER

7b

CHAPMAN HALL/CRC

Risk Analysis in Engineering and Economics

RISK CONTROL METHODS

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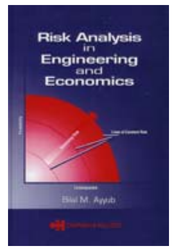

Risk Analysis for Engineering

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Risk-based Maintenance Management

- Maintenance Methodology
  - Maintenance of a structural system can be performed through the use of risk and economic concepts.
  - A marine system is chosen to illustrate the these concepts.
  - The methodology described herein is referred to as Risk-based Optimal Maintenance Management of Ship Structures (ROMMSS) as described by Ayyub, et al. (2002).

Risk-based Maintenance Management

- Maintenance Methodology (cont'd)
  - Systematic, quantitative, qualitative or semi-quantitative approaches for assessing the failure probabilities and consequences of engineering systems are used for this purpose.
  - The ability to quantitatively evaluate these systems helps cut the cost of unnecessary and often expensive re-engineering, repair, strengthening or replacement of components, subsystems and systems.

Risk-based Maintenance Management

- Maintenance Methodology (cont'd)
  - The results of risk analysis can also be utilized in decision analysis methods that are based on cost-benefit tradeoffs.
  - ROMMSS
    - The ROMMSS is essentially a 6-step process that provides a systematic and rational framework for the reduction of total ownership costs for ship structures.
    - The basic steps followed for the ROMMSS strategy are shown in Figure 12.

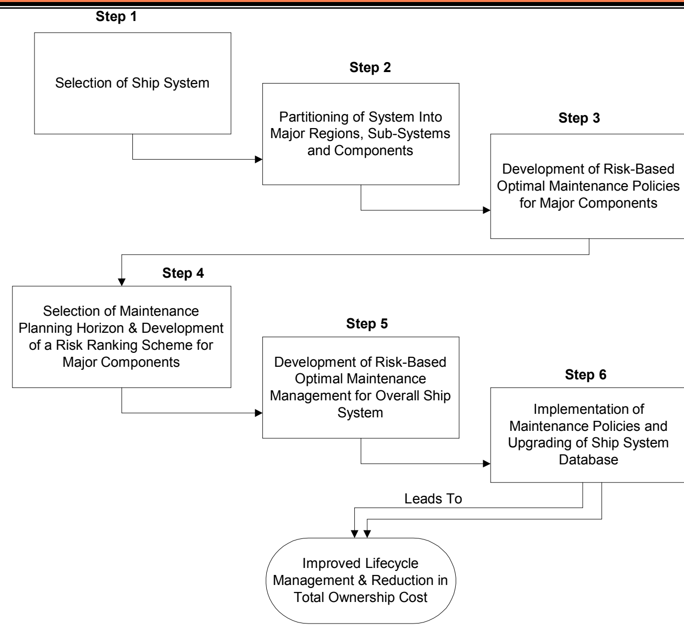

Figure 12. Flowchart for Development of Risk-Based Optimal Maintenance Management of Ship Structures (ROMMSS)

Risk-based Maintenance Management

- Maintenance Methodology (cont'd)
  - The six steps of the ROMMSS strategy are:
    1. Selection of ship or fleet system;
    2. Partitioning of the ship structure into major subsystems and components;
    3. Development of risk-based optimal maintenance policy for major components within a subsystem;
    4. Selection of a time frame for maintenance implementation, and development of risk-ranking scheme;
    5. Development of optimal maintenance scheduling for the overall vessel; and
    6. Implementation of optimal maintenance strategies and updating system condition states and databases.

Risk-based Maintenance Management

- Selection of Ship or Fleet System
  - The first task in ROMMSS involves the selection of a ship system for maintenance.
  - This selection could be a single vessel or an entire class of similar ships.
  - The system and its boundaries must first be identified.
  - The focus herein is on the maintenance of the hull structural system.

Risk-based Maintenance Management

- Selection of Ship or Fleet System (cont'd)
  - The hull system includes
    - longitudinals,
    - stringers,
    - frames,
    - beams,
    - bulkheads,
    - plates,
    - coatings,
    - foundations, and
    - tanks

Risk-based Maintenance Management

- Selection of Ship or Fleet System (cont'd)
  - The hull structural system delineates
    - the internal and external shape of the hull, maintains watertight integrity,
    - ensures environmental safety,
    - and provides protection against physical damage.
  - The boundaries of a hull structural system include
    - the hull,
    - its appendages from (and including) the boot topping down to the keel for the exterior surfaces of the ship,
    - the structural coating, and insulation for the interior and exterior surfaces.

Risk-based Maintenance Management

- Partitioning of the System
  - Components of a typical ship vessel include
    - the main hull form (part of which is below the waterline),
    - single or multiple decks,
    - an engine room,
    - an equipment room,
    - fuel tanks,
    - freshwater tanks,
    - ballast tanks,
    - super-structures, and
    - storage area

Risk-based Maintenance Management

- Partitioning of the System (cont'd)
  - These components experience structural deterioration due to loads from a variety of sources, environmental and otherwise.
  - The maintenance requirements of various components of a ship structure may differ in terms of frequency, type, and cost, even for components within the same region.
  - The presence of structural damages and the uncertainty associated with its impact pose a risk that can affect the overall safety of a vessel.

Risk-based Maintenance Management

- Partitioning of the System (cont'd)
  - The basic steps involved in partitioning a ship structural system are demonstrated in Figure 13.
  - An example of a partitioning scheme for a naval vessel is shown in Figure 14.
  - The structure is first broken into four artificial regions separated by major transverse bulkheads.

Risk-based Maintenance Management

- Partitioning of the System (cont'd)

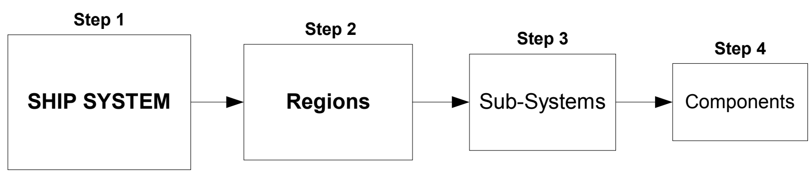

Figure 13. Basic Steps in Partitioning a Ship Structural System

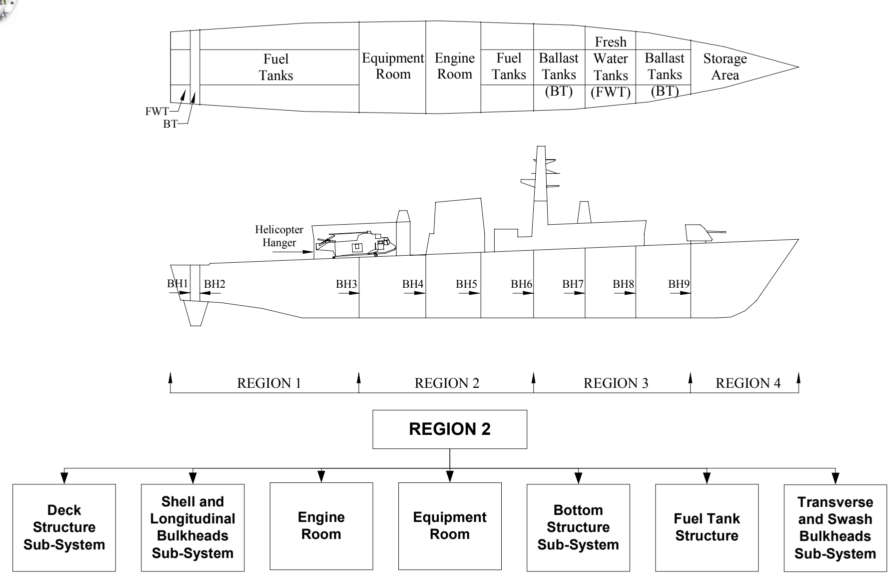

Figure 14. Demonstration of Partitioning Scheme for a Navy Ship

Risk-based Maintenance Management

- Partitioning of the System (cont'd)
  - For example, region 2, which lies between bulkhead number 3 (BH3) and bulkhead number 6 (BH6), has the following major elements:
    - deck structure,
    - hull plating,
    - and longitudinal bulkhead,
    - engine room,
    - equipment room,
    - bottom structure,
    - fuel tank structures, and
    - transverse bulkheads

Risk-based Maintenance Management

- Partitioning of the System (cont'd)
  - These subsystems are further broken down into their major components as shown in Figure 15.
  - A partitioning scheme is also demonstrated in Figures 16 for a typical tanker ship, where the vessel is broken into fore, mid, and aft regions.
  - The major mid-ship structural sub-systems and its components are shown in Figure 17.

Risk-based Maintenance Management

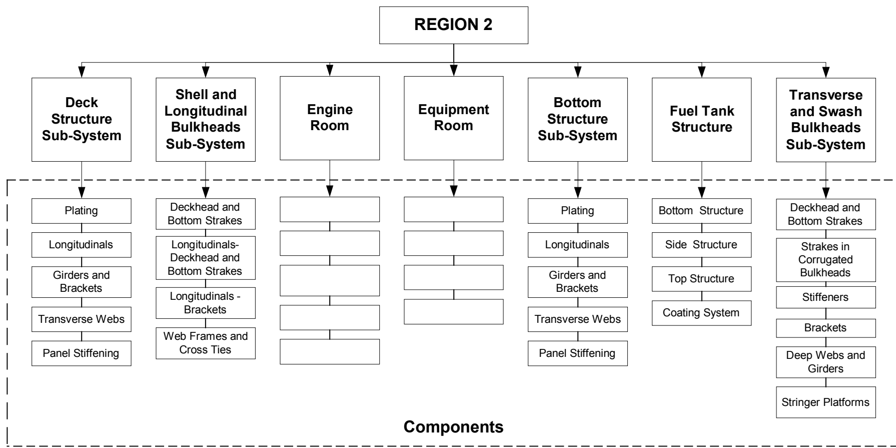

Figure 15. Demonstration of Sub-system Partitioning Scheme for a Navy Ship

Risk-based Maintenance Management

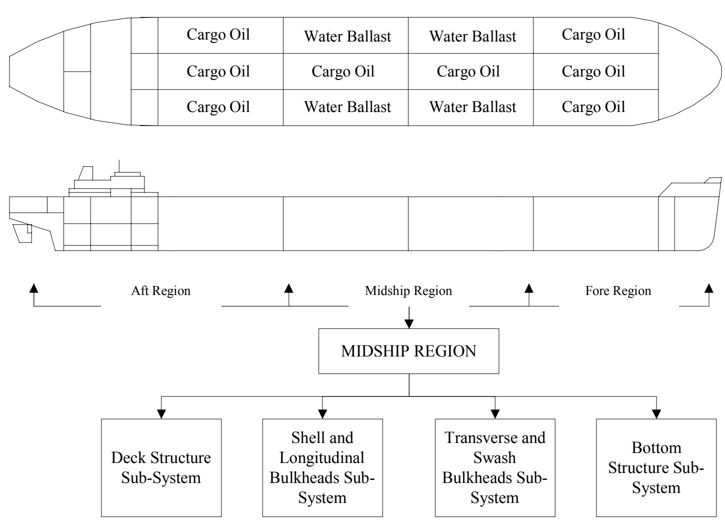

Figure 16. Demonstration of Partitioning Scheme for a Tanker Structure

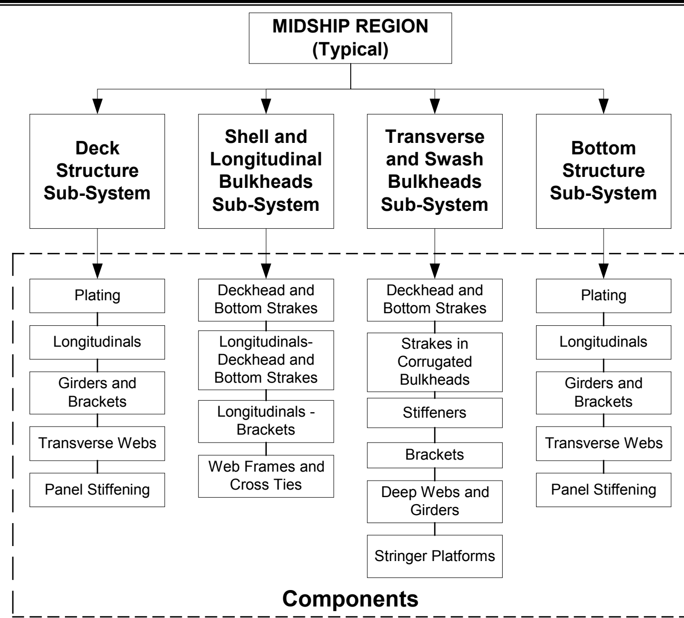

Figure 17. Typical Mid-ship Sub-Systems and Components for Tanker Ship

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components
  - The details of Step 3 of ROMMSS are described here.
  - Figure 18 provides a flowchart for the risk-based optimal maintenance of individual components.
  - Each of the essential steps outlined in the flow chart is discussed in the following sub-sections.

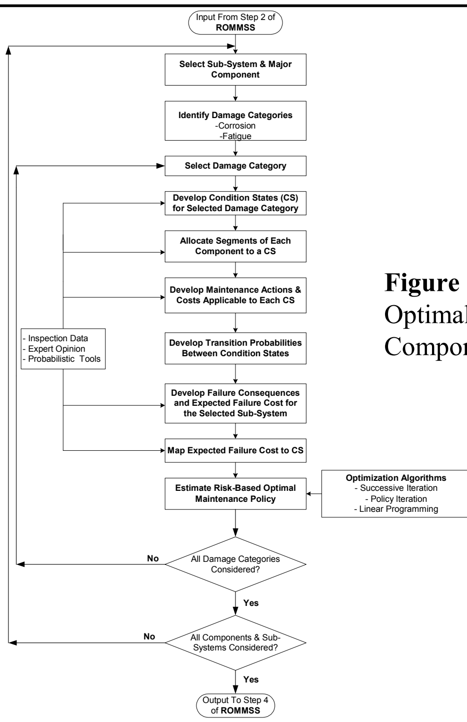

Figure 18. Flowchart for Risk-based Optimal Maintenance Policy for Major Components

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Selection of a Subsystem and Its Major Components
    - The sub-system must first be identified and then its major component selected.
    - Examples of this process have been presented earlier in Figures 15 and 17.
  - Identification of Damage Categories
    - Several damage categories may be applicable to a major component.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Identification of these categories must place emphasis on those components that have been known to consume an excessive portion of the overall maintenance budget.
  - A review of ship structures maintenance needs shows that with respect to budget consumption, the most prominent damage categories for most components include fatigue cracking and corrosion.
  - ***Fatigue cracks*** are the result of repeated application of stress cycles, which gradually weaken the granular structure of a metal.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - They are typically enhanced by high stresses and are most likely to occur in regions of high stress concentration.
  - ***Corrosion***, on the other hand, is the physical deterioration of a metal as a result of chemical or electrochemical reaction with its environment.
  - The rate of corrosion attack depends on many factors, including heat, acidity, salinity, and the presence of oxygen.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
    - Corrosion generally progresses to different degrees in different locations, but overall result is a gradual reduction in a structure's capacity for load.
  - Development of Condition States
    - Once a system has been broken down into its major sub-systems and components, condition states are employed as a measure of the degree of damage experienced by segments of a given component.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
    - Condition states serve to rank the level of damage severity among segments.
    - The level of damage could range from 'good as new' or '**intact**' to '**failure**'.
    - The condition states for a particular type of damage have to be defined.
    - Two examples of corrosion-based condition states currently used by various classification societies, navies and inspectors are illustrated in Tables 11 and 12.

Risk-based Maintenance Management

Table 11. Condition States for Corrosion Damage (Visual Observation)

Condition State	Name	Description
1	No Corrosion	Paint/Protection system is sound and functioning as intended
2	Low Corrosion	Surface rust or freckled rust has either formed or is in the process of forming.
3	Medium Corrosion	Surface or freckled rust is prevalent and metal is exposed
4	Active/High Corrosion	Corrosion is present and active, and a significant portion of metal is exposed
5	Section Loss	Corrosion has caused section loss sufficient to warrant structural analysis to ascertain the effect of the damage.

Risk-based Maintenance Management

Table 12. Condition States for Corrosion Damage (Measured Thickness Loss)

Condition State	Name	Description
1	No Corrosion	Paint/Protection system is sound and functioning as intended
2	Surface Corrosion	Less that 10% of metal thickness has been attacked by corrosion
3	Moderate Corrosion	Metal thickness loss is between 10% and 25%
4	Deep Corrosion	Metal thickness loss is between 25% and 50%
5	Excessive Corrosion	Metal thickness reduced to less than 50% of original thickness

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Table 11 represents an example of condition states allocated based on a visual observation.
  - Table 12 represents condition states allocated based on measured values of material thickness.
  - In addition, condition states for any damage category can be defined through elicitation of subject matter experts.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Allocation of Component Percentages in Each Condition State
    - Inspections are periodically conducted in order to ascertain the damaged condition states of major components of ship structures.
    - Generally, basic defects such as cracking, corrosion, coating breakdown, and buckling are sought for and documented during inspections.
    - An inspection could be conducted either _visually_ or using more sophisticated equipment such as _ultrasonic_ thickness gauging.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - The purpose of this step is to allocate the percentage of a major component to the condition state corresponding to the damage it has experienced.
  - This task should be performed using the data obtained during the inspection.
  - Exact values of the percentage allocated to each condition state are not required for optimal performance of the current methodology.
  - The methodology is robust enough to handle such uncertainties and inexact values.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - This percentage allocation represents the current distribution of the condition states for a particular component.
  - For example, in a condition state allocation scheme consisting of 5 condition states, the following vector represents the percentage breakdown of the current condition states (i.e., t = 0):

$$S^0 = \left[S_1^0, S_2^0, S_3^0, S_4^0, S_5^0\right] \qquad (36)$$

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - The total percentage of components allocated to a condition state vector at any time always adds to 100.
  - Unfortunately, in ship structural systems, current inspection data and records may not be available with which to develop condition state distributions.
  - In such instances, the help of subject matter experts (SME's) may be elicited to establish current condition state distributions.
  - Factors such as the age and travel route of the vessel, and also the location of the components must be taken into consideration when eliciting SME's.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - A maximum value should be specified for the percentage of the components permitted to be allocated to the worst condition state at any time.
  - This threshold value should be based on Flag Administration Officer and Classification Society requirements.
  - Referring to Eq. 36, S_5^0 must be no greater than s_L (i.e., $S_5^0 \leq$ sL).

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Maintenance Actions and Maintenance Costs
    - Maintenance and repair actions that can be applied to various segments of a component depend not only on the damage category, but also the location of the component and the condition states of the component.
    - The cost of these actions can differ significantly.
    - For example, consider the corrosion problem defined previously. Possible maintenance actions include spot blasting, welding, patch coating, addition and maintenance of sacrificial anodes, and section replacement.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
    - In general, the cost of maintenance action increases with the severity of a condition state.
    - A risk-based optimal maintenance system must seek to minimize the cost of maintenance.
    - Cost of maintenance actions could include
      - materials,
      - labor costs, and
      - the cost of steel and anode replacement .
    - The unit costs should be based on the dimensions of the component (area, volume or length).

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - A summary of potential maintenance actions and associated costs for the corrosion problem considered previously is shown in Table 13.
  - The associated cost designation, $C(a,b)$, reads as follows: "the maintenance cost associated with condition state a and maintenance action b."
  - It should be noted from Table 13 that every condition state has a 'No Repair' maintenance action. There is also an associated expected failure cost due to the risk of being in a particular condition state. This cost is estimated at a subsequent step.

Table 13. Demonstrative Maintenance Actions and Associated Costs

Condition State (CS)	Percentage of Component in CS (PCS)	Possible Maintenance Action (MA)	Expected Unit Cost of Maintenance Action (EUCMA) $
1	S_1^0	1-No Repair	0
		2-Monitor	$C(1,2)$
2	S_2^0	3-No Repair	0
		4-Monitor	$C(2,4)$
		5- Spot Blast/Patch Coating	$C(2,5)$
3	S_3^0	6-No Repair	0
		7-Spot Blast/Patch Coating	$C(3,7)$
		8-Spot Blast/ Weld Cover Plate/Patch Coating	$C(3,8)$
4	S_4^0	9-No Repair	0
		10-Cut Out/Weld New Plate/Spot Blast/Patch Coating	$C(4,10)$
		11-Add/Maintain Sacrificial Anode	$C(4,11)$
5	S_5^0	12-No Repair	0
		13-Cut Out/Weld New Plate/Spot Blast/Patch Coating	$C(5,13)$
		14- Replace Component	$C(5,14)$

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Transition Probabilities for Cases without Maintenance Actions
    - Ship structural components tend to deteriorate when no maintenance actions are taken.
    - A model must therefore be developed to estimate the deterioration rates of components under such circumstances.
    - The model must have the capability to quantify the uncertainty inherent in such predictions.
    - Furthermore, the prediction model must have the capability to incorporate results from actual experience, and to update parameter values when more data becomes available.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
    - A probabilistic Markov chain model, which quantifies uncertainty, is adopted in this study.
    - It estimates the likelihood that a component, in a given condition state, would make a transition to an inferior condition state within a specified period.
    - An example of the Markov chain model is shown in Figure 19.
    - Such Markov chain modeling has been used in bridge management systems for maintenance planning developed by the Federal Highway Administration and utilized by many states.

Risk-based Maintenance Management

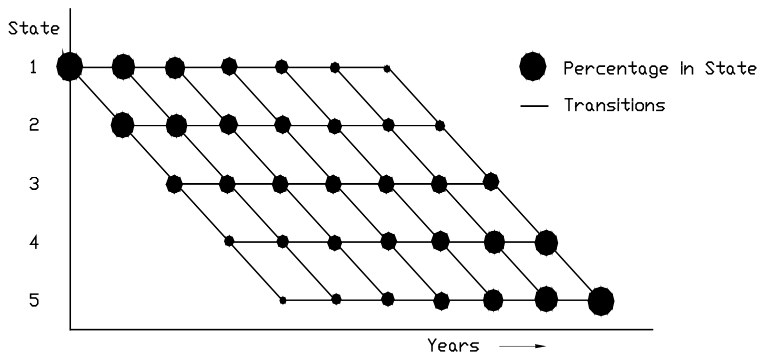

Figure 19. Demonstration of Markov Chain Transition between Condition States for Cases without Maintenance Actions

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)

Suppose we have all of a component in state 1, how long will it take for 50% of them to deteriorate to state 2 if no maintenance action is taken?

- Taking the above question as an example, the probability of transition, i.e., deterioration, from condition state 1 to condition state 2, P_{12}, can be computed using

$$P_{12} = 1 - 0.5^{1/T_1} \qquad (37)$$

T_1 = is the number of years used to calculate transition probabilities

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - The optimal maintenance policy selections are based on the theory of discounted dynamic programming.
  - Let X_n denote the state of the process at time n, and an the action chosen, the previous statement implies that:

$$P\left(x_{n+1}=j \middle| x_0, a_0, \ldots, x_1, a_1 \ldots x_n = i, a_n = a\right) = P_{ij}(a) \qquad (38)$$

  - Thus the costs and transition probabilities are functions of only the previous state and subsequent action, assuming that all costs are bounded.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - To select from the potential actions, some policy must be followed.
  - An important class of all policies is the class of stationary policies.
  - A policy f is called stationary if it is non-random, and the action it chooses at time t depends only on the state of the process at time t; whenever in state i, $f(i)$ is chosen.
  - Thus, when a stationary policy is employed, then the sequence of states $(X_n, n = 0,1,2,\ldots)$ forms a Markov chain.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - To find the optimal policy, a criterion for such optimization must be chosen.
  - If we choose as our criterion the total expected return on invested dollars, and discount future costs by a discount factor α, (such that $0 < \alpha < 1$), then among all policies π, we attempt to minimize:

$$V_\pi(i) = E_\pi\left[\sum_{n=0}^{\infty} c(i_n, a_n)\alpha^n \middle| x_0 = i\right] \qquad (39)$$

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - A policy π^* is said to be α-optimal if $V_\pi^* \le V_p(i)$ for all i and π.
  - The main result of dynamic programming, i.e., the optimality equation, yields a functional equation satisfied by $V(i)$ as follows:

$$V(i) = \min_a \left[c(i_n, a_n) + \alpha \sum_j P_{ij}(a) V(j) \right] \qquad (40)$$

  - An important result of dynamic programming proves that the policy determined by the optimality Eq. 40.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - if f is a stationary policy that, when the process is in state i, selects an action that minimizes the right hand side of Eq. 40, then:

$$V_f(i) = V(i) \text{ for all } i \qquad (41)$$

  - It is also true that V is the unique bounded solution of the optimality equation.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Failure Consequences and Expected Failure Cost
    - The level of risk depends on the consequences of subsystem failure.
    - The consequences of failure could range from unplanned repair, unavailability, and environmental pollution to reduction or loss of serviceability.
    - This task is aimed at identifying and streamlining the consequences of failure associated with a subsystem.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - The approach proposed herein assigns importance factors to the various components that make up the subsystem. More specifically, this step involves:
    - Identification and categorization of failure consequence for a subsystem. An example is shown in Table 14.
    - Development of a rating scheme for the various components of a subsystem. The rating scheme ranks the components of a subsystem in terms of their degree of importance to the overall structural integrity, water-tightness and functional requirements of the subsystem. A rating scheme can be developed as shown in Table 15.

Risk-based Maintenance Management

Table 14. Example of Possible Consequences of Subsystem Failure

Consequence of Failure	Consequence Cost Per Incident $
1. Minor Structural Failure	C_1 = Minor Unplanned Repair Cost
2. Reduction/Loss of Serviceability	C_2 = Economic Cost due to Loss of Serviceability
3. Major Structural Failure	C_3 = Substantial Unplanned Repair Cost/ Economic Cost
4. Major Oil Spill, Leak, or other form of Environmental Pollution	C_4 = Environmental Cleaning/Litigation Cost

Risk-based Maintenance Management

Table 15. Sample Ranking Scheme for a Typical Subsystem

Bottom Structure Components	(Level of Importance 1-4) 1-Low Importance 4-High Importance
Bottom Plating	4
Bottom Longitudinals	4
Bottom Girders and Brackets	4
Bottom Transverse Webs	3
Panel Stiffening	4

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  – Mapping the cost of failure to the 'no repair' action that exists within a given condition state (see Table 13). The goal is to estimate the likelihood of whether operating in a particular condition state will increase or reduce the chances of incurring a particular failure cost. Subject matter experts can again be called upon to estimate this probability. The probability estimation process must be cast in such a way that experts can supply subjective information that can be translated into numerical values. An example of a probabilistic translation scheme is shown in Table 16.

Risk-based Maintenance Management

Table 16. An Example of a Probabilistic Translation Scheme

Probability	Value
Low	10^{-6}
Medium	10^{-4}
High	10^{-2}
Very High	10^{-1}

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - In order to perform such mapping operations, an appropriate survey of questions must be developed. An example question could be as follows:

Suppose a component is in state 1 (new state), what is the likelihood that it will experience an unplanned repair during its first year of service?

  - The findings can then be summarized to arrive at an expected failure cost as shown in Table 17.
  - It is evident that the procedure can become quite involved and must therefore be computerized to achieve cost-effectiveness.

Risk-based Maintenance Management

Table 17. An Example of a Mapping Condition States To Failure Cost

Condition State	Action	Probability of Failure Consequence	Expected Unit Failure Cost (EUFC)
1	No Repair	P_{1C_1} P_{1C_2} P_{1C_3} P_{1C_4}	$R_1 = P_{1C_1}C_1 + P_{1C_2}C_2 + P_{1C_3}C_3 + P_{1C_4}C_4$
2	No Repair	P_{2C_1} P_{2C_2} P_{2C_3} P_{2C_4}	$R_2 = P_{2C_1}C_1 + P_{2C_2}C_2 + P_{2C_3}C_3 + P_{2C_4}C_4$
3	No Repair	P_{3C_1} P_{3C_2} P_{3C_3} P_{3C_4}	$R_3 = P_{3C_1}C_1 + P_{3C_2}C_2 + P_{3C_3}C_3 + P_{3C_4}C_4$
4	No Repair	P_{4C_1} P_{4C_2} P_{4C_3} P_{4C_4}	$R_4 = P_{4C_1}C_1 + P_{4C_2}C_2 + P_{4C_3}C_3 + P_{4C_4}C_4$
5	No Repair	P_{5C_1} P_{5C_2} P_{5C_3} P_{5C_4}	$R_5 = P_{5C_1}C_1 + P_{5C_2}C_2 + P_{5C_3}C_3 + P_{5C_4}C_4$

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Transition Probabilities for Cases with Maintenance Actions
    - Assessing the quality of repair is highly subjective, as it depends not only on the personnel involved, but also the shipyard that is used.
    - Therefore, a model must be developed to not only estimate the improvement of a component after a maintenance action has been taken, but also quantify the uncertainty inherent in such improvements.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - The prediction model must have the capability to incorporate results from actual experience and also update its parameters when more data becomes available.
  - A Markov chain transition probability model, which quantifies uncertainty, is again adopted in this section.
  - Elicitation of subject matter experts is currently the only approach to estimating transition among states when maintenance actions are taken.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - A suitable survey of subject matter experts questions should be compiled such that expert opinions can easily be translated to transition probabilities.
  - An example question could be:

Suppose a group of components are operating in state 3 and a particular maintenance action is taken, what then, are the percentages of components that, as a result, improve to states 1 and 2, respectively, immediately after the action??

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - A computerized elicitation program can be developed to generate and use the survey to address the effectiveness of possible repair actions for the various major components of ship structures.
  - Table 18 below summarizes the outcome of implementation of the above steps.
  - Failure probabilities can be assessed using models provided in Chapter 4.

Risk-based Maintenance Management

Table 18. Implementation of Maintenance Actions to Estimate Failure Cost

CS	PCS	Maintenance Action Number	Transition Probabilities Among States					Expected Unit Maintenance Cost	Expected Failure Cost
			1	2	3	4	5		
1	s_{10}	1	$P_{11}(1)$	$P_{12}(1)$	$P_{13}(1)$	$P_{14}(1)$	$P_{15}(1)$	0	R_1
		2	$P_{11}(2)$	$P_{12}(2)$	$P_{13}(2)$	$P_{14}(2)$	$P_{15}(2)$	C(1,2)	
		3	$P_{21}(3)$	$P_{22}(3)$	$P_{23}(3)$	$P_{24}(3)$	$P_{25}(3)$	C(2,3)	
2	s_{20}	4	$P_{21}(4)$	$P_{22}(4)$	$P_{23}(4)$	$P_{24}(4)$	$P_{25}(4)$	C(2,4)	R_2
		5	$P_{21}(5)$	$P_{22}(5)$	$P_{23}(5)$	$P_{24}(5)$	$P_{25}(5)$	C(2,5)	
		6	$P_{21}(6)$	$P_{22}(6)$	$P_{23}(6)$	$P_{24}(6)$	$P_{25}(6)$	C(3,6)	
3	s_{30}	7	$P_{31}(7)$	$P_{32}(7)$	$P_{33}(7)$	$P_{34}(7)$	$P_{35}(7)$	C(3,7)	R_3
		8	$P_{31}(8)$	$P_{32}(8)$	$P_{33}(8)$	$P_{34}(8)$	$P_{35}(8)$	C(3,8)	
		9	$P_{41}(9)$	$P_{42}(9)$	$P_{43}(9)$	$P_{44}(9)$	$P_{45}(9)$	C(4,9)	
4	s_{40}	10	$P_{41}(10)$	$P_{42}(10)$	$P_{43}(10)$	$P_{44}(10)$	$P_{45}(10)$	C(4,10)	R_4
		11	$P_{41}(11)$	$P_{42}(11)$	$P_{43}(11)$	$P_{44}(11)$	$P_{45}(11)$	C(4,11)	
		12	$P_{51}(12)$	$P_{52}(12)$	$P_{53}(12)$	$P_{54}(12)$	$P_{55}(12)$	C(5,12)	
5	s_{50}	13	$P_{51}(13)$	$P_{52}(13)$	$P_{53}(13)$	$P_{54}(13)$	$P_{55}(13)$	C(5,13)	R_5
		14	$P_{51}(14)$	$P_{52}(14)$	$P_{53}(14)$	$P_{54}(14)$	$P_{55}(14)$	C(5,14)	

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Risked-Based Optimal Maintenance Policy
    - The data needed for determining risk based optimal maintenance policy for a component are summarized in Table 18.
    - The objective of this particular task is to find, for a component under an environment or damage category, the maintenance policy that minimizes the maintenance cost while maintaining the system below an acceptable risk level in the long run.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
    - The optimal maintenance strategy is the one that incurs the minimum total cost.
    - The two main implications of an optimal policy are:
      - Delaying recommended actions will be more expensive in the long term; and
      - Performing additional maintenance actions, which are considered in the model but not recommended, will result in an increase in overall maintenance costs.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - Four important things occur periodically with major components of a ship structure:
    - Components deteriorate, resulting in transition from one condition state to a worse condition state;
    - The existence of segments of a component in various condition states means there is a risk of failure, which translates into expected failure costs;
    - Maintenance actions (both minor yearly repairs and major dry-dock repairs) are executed, thereby incurring costs; and
    - Implementation of maintenance actions yields an improvement in the condition state of a component.

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - This information is summarized in Table 18.
  - A risk based optimal maintenance policy uses the above information to prescribe a set of maintenance actions that minimizes maintenance costs while ensuring the component is not subjected to an unacceptable risk of failure.
  - This policy may be formulated again using the Markov decision model.

CHAPTER 7b. RISK CONTROL METHODS Slide No. 64

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - The effect of a set of maintenance actions and the cost of those actions are propagated through a Markov chain via appropriate transition probabilities.
  - The problem can be stated as follows for each component's condition state:
    - find the set of maintenance actions that will minimize the total discounted vessel ownership costs over the long term, given that the component may deteriorate and assuming that the maintenance policy continues to be followed.

CHAPTER 7b. RISK CONTROL METHODS Slide No. 65

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - The problem essentially requires minimization of the following relation

$$V(i) = C(i,a) + \alpha \sum_j P_{ij}(a) V(j) \qquad (42)$$

i	= condition state observed today
j	= condition state prediction a set number of years in the future
$V(i)$	= long-term cost expected as a result of being in state i today
$C(i,a)$	= initial cost of action a taken in state i
α	= discount factor for a cost incurred a set number of years in the future
P_{ij}(a)	= transition probability of condition state j to condition state i under action a
$V(j)$	= long-term cost expected as of next year if transition to condition state j occurs

Risk-based Maintenance Management

- Development of Optimal Maintenance Policy for Components (cont'd)
  - The above formulation is a dynamic programming problem for which there are a variety of solution techniques available, including:
    1. Method of successive iteration,
    2. Policy iteration, and
    3. Linear programming formulation.
  - These methods are beyond the scope of this section and are not covered.
  - Once the best maintenance strategy is chosen, its optimality must then be demonstrated.

Risk-based Maintenance Management

- Maintenance Implementation, and Development of Risk-Ranking Scheme
  - The selection of an optimal maintenance management policy is not only a function of potential maintenance actions, but also, and perhaps more importantly, the scheduling for implementation of recommended maintenance actions.
  - In developing an optimal policy for maintenance management, a suitable time frame for the implementation of maintenance actions must be chosen.

Risk-based Maintenance Management

- Maintenance Implementation, and Development of Risk-Ranking Scheme (cont'd)
  – Selection of such a time frame could be dictated by Flag Administration Officer or Classification Society requirements, elicitation of subject matter experts, engineering experience, and current practice, with values of 5 to 7 years being typical.
  – Once a planning time frame has been selected, criteria must be chosen upon which to base maintenance implementation decisions.

Risk-based Maintenance Management

- Maintenance Implementation, and Development of Risk-Ranking Scheme (cont'd)
  – Implementation of maintenance actions for various system components may be based on such factors as maintenance costs or potential risk/failure costs.
  – Also, implementation may be based upon condition state deterioration for each component.
  – Using a combination of Flag Administration Officer and Classification Society requirements, SME elicitation, and experience, thresholds may be set for condition state deterioration of major structural components.

Risk-based Maintenance Management

- Maintenance Implementation, and Development of Risk-Ranking Scheme (cont'd)
  - Alternative maintenance implementation schedules may then be compared, considering factors such as
    - cost savings,
    - risk reduction,
    - and condition state improvement, and
    - any effects that delayed implementation may have on these factors

Risk-based Maintenance Management

- Maintenance Implementation, and Development of Risk-Ranking Scheme (cont'd)
  - Combining this information with specific budgetary resources and risk tolerance levels of individual owner/operators, optimal maintenance schedules for each component may be ranked to assess both the relative urgency with which each must be implemented and the ability of each to meet the aforementioned criteria.

Risk-based Maintenance Management

- Optimal Maintenance Scheduling for the Overall Vessel
  - Upon selection of a suitable ranking criterion, the potential maintenance schedules for the various components should then be ranked using the selected criteria in conjunction with the available budget and threshold levels for risk and condition state deterioration.
  - The maintenance policies for individual components, developed in Step 3 of ROMMSS, are optimal for only those components.

Risk-based Maintenance Management

- Optimal Maintenance Scheduling for the Overall Vessel (cont'd)
  - When the budgetary resources are unlimited, the optimal maintenance policies for individual components can be scheduled for implementation without delay.
  - Note that budgetary resources are always limited, thus an optimal maintenance strategy for the overall vessel must employ some sort of ranking scheme, focused on allocating scarce budgetary resources to those components with the most urgent needs, as defined in Step 4 of ROMMSS.

Risk-based Maintenance Management

- Optimal Maintenance Scheduling for the Overall Vessel (cont'd)
  – Ship structural maintenance is somewhat unique in the sense that major repair actions typically require dry-docking of the vessel for extended periods of time, during which normal operational commitments of the vessel must be suspended.
  – A maintenance implementation schedule ignorant of dry-docking could prove disastrous in terms of unnecessary ownership costs.

Risk-based Maintenance Management

- Optimal Maintenance Scheduling for the Overall Vessel (cont'd)
  – The total maintenance and risk costs, and condition state deterioration for the system within the planning horizon should be closely examined.
  – Scheduling dry-docking for only those components requiring extensive repair may help to further reduce unnecessary down time for the vessel.

Risk-based Maintenance Management

- Implementation of Maintenance Strategies and Updating System
  - Thus far, the ROMMSS procedures outlined previously have not been physical in nature, but rather computational, employing an extensive network of modules and databases for condition state transition matrices, maintenance and risk costs, risk and condition state thresholds, expert opinions, Flag Administration Officer and Classification Society requirements, shipyard data, and budgetary resources.

Risk-based Maintenance Management

- Implementation of Maintenance Strategies and Updating System (cont'd)
  - These databases have been used to then recommend an optimal maintenance management strategy, both in terms of repair action and scheduling.
  - Upon recommendation of an optimal maintenance plan by ROMMSS, it is the owner's discretion regarding the physical implementation of its strategies.
  - As the strategies are implemented, the ship structural system database should be continually updated.

Risk-based Maintenance Management

- An Application: Optimal Maintenance Management of Ship Structures
  - The conceptual framework for the Risk-based Optimal Maintenance Management of Ship Structures, ROMMSS, is demonstrated with an example problem herein.
  - When fully implemented as a software tool, ROMMSS can consist of a database and a computational tool that ship designers, owners, managers and operators can use to make long-term lifecycle management decisions to reduce operational costs.

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  - The assumed initial condition state distributions for each of the four components are given in Table 19.
  - The assumed unit maintenance costs and unit failure/risk costs for each component are summarized in Tables 20 and 21, respectively.
  - The transition probability matrices for the four major components are presented in Tables 22 through 25.

Risk-based Maintenance Management

Table 19. Assumed Initial Distribution of Component Condition States

Year 1	CS1	CS2	CS3	CS4	CS5
Component 1	45%	45%	5%	5%	0%
Component 2	35%	25%	30%	5%	5%
Component 3	5%	20%	45%	15%	15%
Component 4	10%	45%	35%	5%	5%

Risk-based Maintenance Management

Table 20. Unit Maintenance Cost for Components

Condition State	Maintenance Action	Component 1	Component 2	Component 3	Component 4
CS1	1	$0	$0	$0	$0
	2	$1,000	$1,100	$1,000	$1,200
CS2	3	$0	$0	$0	$0
	4	$1,000	$1,100	$1,100	$1,200
	5	$2,100	$2,200	$2,350	$3,500
CS3	6	$0	$0	$0	$0
	7	$2,000	$2,200	$2,300	$3,650
	8	$2,500	$2,750	$2,750	$3,750
CS4	9	$0	$0	$0	$0
	10	$3,500	$3,850	$2,750	$4,950
	11	$2,500	$2,750	$3,850	$4,850
CS5	12	$0	$0	$0	$0
	13	$3,500	$3,850	$3,850	$4,850
	14	$4,000	$4,400	$4,400	$5,489

Risk-based Maintenance Management

Table 21. Unit Failure/Risk Cost for Components

Component	CS1	CS2	CS3	CS4	CS5
Component 1	$500	$1,500	$3,500	$4,500	$6,500
Component 2	$550	$1,650	$3,850	$4,950	$7,100
Component 3	$550	$1,650	$3,850	$4,950	$7,100
Component 4	$550	$1,650	$3,850	$6,153	$8,178

Risk-based Maintenance Management

Table 22. Transition Probabilities for Component 1

Condition State	Maintenance Action	CS1	CS2	CS3	CS4	CS5
CS1	1	90%	10%	0%	0%	0%
	2	90%	10%	0%	0%	0%
CS2	3	0%	80%	20%	0%	0%
	4	0%	80%	20%	0%	0%
	5	70%	30%	0%	0%	0%
CS3	6	0%	0%	70%	30%	0%
	7	70%	30%	0%	0%	0%
	8	80%	15%	5%	0%	0%
CS4	9	0%	0%	0%	65%	35%
	10	65%	20%	10%	5%	0%
	11	85%	10%	3%	2%	0%
CS5	12	0%	0%	0%	0%	100%
	13	65%	20%	10%	5%	0%
	14	80%	10%	10%	0%	0%

Risk-based Maintenance Management

Table 23. Transition Probabilities for Component 2

Condition State	Maintenance Action	CS1	CS2	CS3	CS4	CS5
CS1	1	85%	15%	0%	0%	0%
	2	95%	5%	0%	0%	0%
CS2	3	0%	75%	25%	0%	0%
	4	0%	75%	25%	0%	0%
	5	70%	30%	0%	0%	0%
CS3	6	0%	0%	65%	35%	0%
	7	70%	30%	0%	0%	0%
	8	80%	15%	5%	0%	0%
CS4	9	0%	0%	0%	60%	40%
	10	85%	10%	3%	2%	0%
	11	75%	25%	0%	0%	0%
CS5	12	0%	0%	0%	0%	100%
	13	65%	20%	10%	5%	0%
	14	95%	5%	0%	0%	0%

Risk-based Maintenance Management

Table 24. Transition Probabilities for Component 3

Condition State	Maintenance Action	CS1	CS2	CS3	CS4	CS5
CS1	1	85%	15%	0%	0%	0%
	2	95%	5%	0%	0%	0%
CS2	3	0%	82%	18%	0%	0%
	4	0%	82%	18%	0%	0%
	5	70%	30%	0%	0%	0%
CS3	6	0%	0%	65%	35%	0%
	7	80%	20%	0%	0%	0%
	8	85%	15%	0%	0%	0%
CS4	9	0%	0%	0%	60%	40%
	10	85%	10%	3%	2%	0%
	11	75%	25%	0%	0%	0%
CS5	12	0%	0%	0%	0%	100%
	13	55%	0%	0%	45%	0%
	14	95%	5%	0%	0%	0%

Risk-based Maintenance Management

Table 25. Transition Probabilities for Component 4

Condition State	Maintenance Action	CS1	CS2	CS3	CS4	CS5
CS1	1	85%	15%	0%	0%	0%
	2	85%	15%	0%	0%	0%
CS2	3	0%	82%	18%	0%	0%
	4	0%	82%	18%	0%	0%
	5	80%	10%	10%	0%	0%
CS3	6	0%	0%	65%	35%	0%
	7	80%	20%	0%	0%	0%
	8	83%	11%	6%	0%	0%
CS4	9	0%	0%	0%	60%	40%
	10	85%	10%	3%	2%	0%
	11	84%	16%	0%	0%	0%
CS5	12	0%	0%	0%	0%	100%
	13	85%	0%	15%	0%	0%
	14	95%	5%	0%	0%	0%

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  - A ROMMSS-based maintenance management analysis of a vessel is performed with a number of objectives in mind. For the purpose of demonstration, the objectives include

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  – A ROMMSS-based maintenance management analysis of a vessel is performed with a number of objectives in mind. For the purpose of demonstration, the objectives include
    - Determination of the optimal maintenance strategies for each of the defined components in each condition state;
    - Determination of the condition states of each component in the event that their individual optimal maintenance policies are either implemented immediately, or delayed for one, two, three, four or five years within the planning period;

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
    - Determination of the risk/failure cost associated with delayed implementation of optimal maintenance policies;
    - Determination of the increase/decrease in maintenance cost associated with delayed implementation of optimal maintenance actions;
    - Ranking of the relative importance of the components maintenance schedule, based on failure/risk cost, maintenance cost, and condition state deterioration, or a combination thereof; and
    - Determination of the optimal time for scheduling a major dry dock repair for the vessel.

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  - In order to proceed with the demonstration of other ROMMSS features, the optimal policies that will be assumed for each component in the current example are summarized in Table 26.

Risk-based Maintenance Management

Table 26. Assumed Long Term Optimal Maintenance Policies for Components

Component	CS1	CS2	CS3	CS4	CS5
Component 1	1	5	7	11	13
Component 2	1	5	7	11	14
Component 3	1	5	7	10	14
Component 4	1	5	7	11	13

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  - For the sake of simplicity in demonstration, the optimal policies at each condition state are assumed to be similar for all components as follows based on Table 13:

Condition State	Maintenance Action (MA)
1	No Repair (MA1)
2	Spot Blast/Patch Coating (MA 5)
3	Spot Blast/Patch Coating (MA 7)
4	Cut Out/Weld New Plate/Spot Blast/Patch Coating (MA10) or Add/Maintain Sacrificial Anode (MA 11)
5	Cut Out/Weld New Plate/Spot Blast/Patch Coating (MA13) or Replace Component (MA 14)

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  - Tables 27 through 30 summarize the component condition states prior to implementation of ROMMSS optimal maintenance policies in the event that policy implementation is delayed for one, two, three, or four years, respectively.

Risk-based Maintenance Management

Table 27. Condition State Distribution if Implementation of Optimal Maintenance Policies is Delayed 1 Year

Year 2	CS1	CS2	CS3	CS4	CS5
Component 1	41%	41%	13%	5%	2%
Component 2	30%	24%	26%	14%	7%
Component 3	4%	17%	33%	25%	21%
Component 4	9%	38%	31%	15%	7%

Risk-based Maintenance Management

Table 28. Condition State Distribution if Implementation of Optimal Maintenance Policies is Delayed 2 Years

Year 3	CS1	CS2	CS3	CS4	CS5
Component 1	36%	36%	16%	8%	5%
Component 2	26%	22%	23%	16%	14%
Component 3	4%	15%	25%	24%	32%
Component 4	7%	33%	26%	19%	15%

Risk-based Maintenance Management

Table 29. Condition State Distribution if Implementation of Optimal Maintenance Policies is Delayed 3 Years

Year 4	CS1	CS2	CS3	CS4	CS5
Component 1	33%	32%	17%	10%	8%
Component 2	22%	20%	20%	17%	21%
Component 3	3%	14%	19%	22%	42%
Component 4	6%	29%	23%	19%	23%

Risk-based Maintenance Management

Table 30. Condition State Distribution if Implementation of Optimal Maintenance Policies is Delayed 4 Years

Year 5	CS1	CS2	CS3	CS4	CS5
Component 1	29%	28%	18%	12%	12%
Component 2	19%	18%	18%	17%	28%
Component 3	3%	12%	15%	19%	51%
Component 4	6%	25%	20%	19%	31%

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  - Figure 20 compares all components based on the percentage of each in condition state 5 (CS5) during each year of the assumed planning period.
  - Recall the unit costs of the potential maintenance actions for each component were previously summarized in Table 24. Those corresponding to the assumed optimal policies are given in Table 31.

Risk-based Maintenance Management

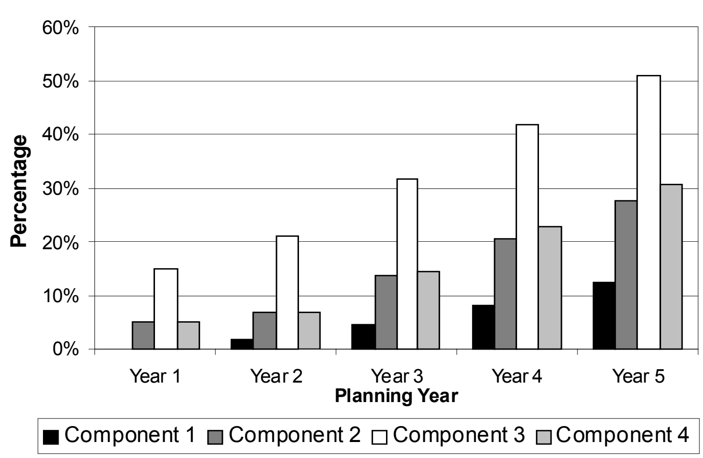

Figure 20. Variation in Percentage of Each Component in the Worst Condition State (CS5) with Delayed Implementation of Optimal Maintenance Policies

Risk-based Maintenance Management

Table 31. Unit Maintenance Cost for Assumed Optimal Policies

Component	CS1	CS2	CS3	CS4	CS5
Component 1	$0	$2,100	$2,000	$2,500	$3,500
Component 2	$0	$2,200	$2,200	$2,750	$4,400
Component 3	$0	$2,350	$2,300	$2,750	$4,400
Component 4	$0	$3,500	$3,650	$4,850	$4,850

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  – Figure 21 presents a summary of the maintenance cost for each component when the recommended maintenance actions are implemented within the first year or delayed for two, three, four or five years.
  – To minimize the risk/failure costs of each component, Figure 22 suggests that repair of Component 3 should be given top priority, followed by Component 4 and Component 2, while repair of Component 1 may be delayed the longest.

Risk-based Maintenance Management

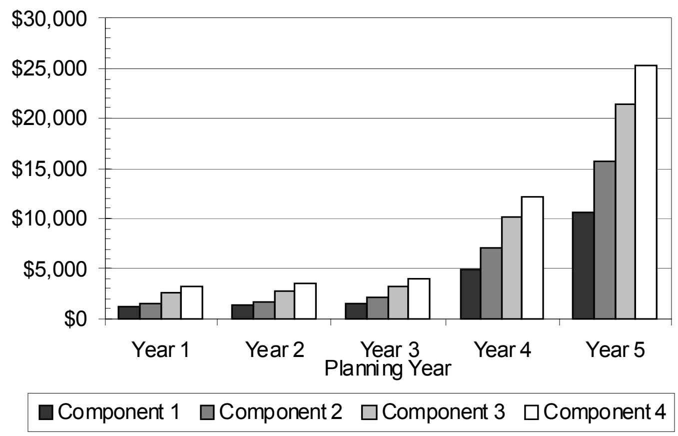

Figure 21. Variation in Yearly Maintenance Cost during the Planning Horizon

Risk-based Maintenance Management

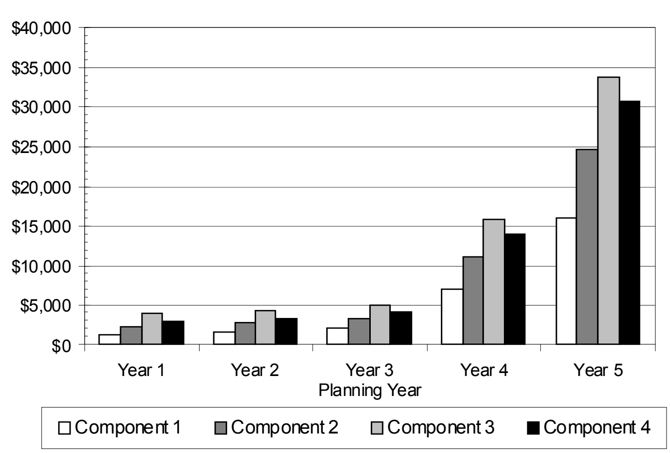

Figure 22. Variation in Component Risk/Failure Costs during the Planning Horizon

Risk-based Maintenance Management

- An Application (cont'd): Optimal Maintenance Management of Ship Structures
  - To facilitate optimization of a schedule for major dry-docking repairs, the total maintenance and risk costs for the system within the planning horizon, as shown in Figure 23, must be closely examined.
  - The figure depicts only a marginal increase in total risk and maintenance costs for the system during the first three years of the assumed planning horizon, with the costs approximately doubling in each of the two remaining years.

Risk-based Maintenance Management

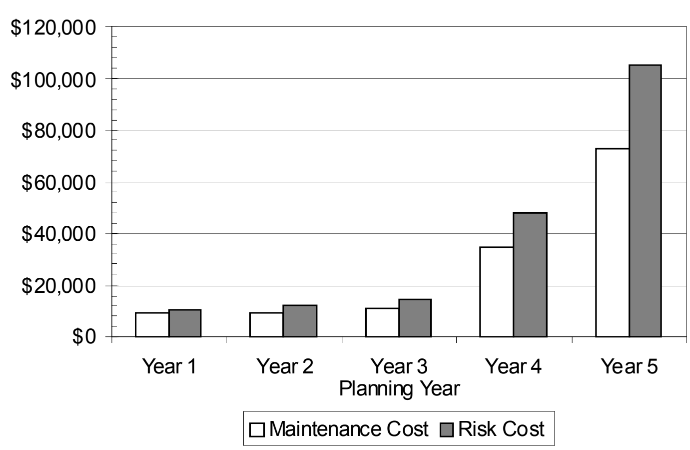

Figure 23. Expected Yearly Risk and Maintenance Costs During the Planning Horizon

Homework Assignment #7

Problems:
7.4
7.5
7.14
7.19
7.24