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Probabilistic ship collision risk and sustainability assessment considering risk attitudes

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ABSTRACT

The disastrous consequences of ship collision necessitate the development of a collision risk-informed assessment procedure that ensures safety and functionality of maritime transportation systems. In this paper, an approach to assess the risk and sustainability associated with ship collision accidents is presented. The probability of ship collision is computed by taking into account traffic data and operational conditions. In this paper, sustainability is quantified considering the detrimental economic, social, and environmental consequences associated with ship collision. The economic, social and environmental metrics are evaluated separately and then social and environmental metrics are converted into an economic metric considering their associated monetary values. Epistemic and aleatory uncertainties associated with damage conditions of ships and consequences are incorporated in this methodology in order to provide a rational assessment of risk and sustainability. Risk attitudes are incorporated within risk analysis by utilizing utility functions. The approach is illustrated on a maritime transportation system in the Delaware River area considering the properties of damaged ships and maritime traffic in this specific region. Ultimately, this approach can aid the decision maker to make informed choices based on risk and sustainability considering risk attitudes.

1. Introduction

Ship collisions can have detrimental impacts on the environment, society, and economy. It is of vital importance to evaluate collision risk in order to plan preventive actions and be sufficiently prepared for possible oil spills and other associated events with negative consequences. The International Maritime Organization (*IMO*) has paid increasing attention to performance-based standards to ensure adequate safety and reliability of ship structures under extreme events [1]. In order to evaluate ship collision risk, it is necessary to develop a methodology that integrates the probability of occurrence of collision in a water area, vulnerability assessment of a ship, and probabilistic consequences of collision on the environment, society, and economy. A wide range of performance indicators can be used for sustainability assessment to reflect social, environmental, and economic impacts [2]. Sustainability can be defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. In general, sustainability can be quantified in terms of economic, social, and environmental metrics [4–6]. Further research must be conducted in order to assess ship collision risk in terms of sustainability and ensure the safety of marine transportation systems.

A predominant part of past studies regarding ship collision focused on determining the probability of this event based on probabilistic scenarios [7–9]. Although these studies described procedures to obtain the probability of ship collision, none has focused on the evaluation of consequences associated with collision. The consequence assessment of damaged ships is crucial for risk-informed decision making after an accident [10]. Very little research has been carried out that properly integrates the probability of ship collision with the consequences associated with collision events into a comprehensive risk assessment methodology [11,12]. The consequences associated with the collision events can be divided into three categories: social, environmental, and economic impacts. Within this paper, these three aspects and their associated uncertainties are incorporated within an approach that can evaluate ship collision risk considering the risk attitude of the decision maker. The probabilistic risk and sustainability associated with ship collision is a relatively new area of research.

The perception of risk is determined by the attitude of the decision maker and is an essential component of risk analysis. Based on

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the willingness of a decision maker, the attitudes toward risk can be classified as risk averse, risk neutral, or risk taking [13]. One of most popular decision theories is the expected utility theory (*UT*) [14]. The alternative with the highest expected utility value is always preferred. Utility theory is incorporated within the decision making framework presented herein. A utility function that measures the value of a particular alternative to the decision maker is established for the criterion under investigation. Utility theory is applied in order to normalize an attribute value to a uniform scale between 0 and 1. Tversky and Kahneman [15] developed cumulative prospective theory, an updated version of prospect theory, which considers the decision maker's risk attitude. The effects of the degree of risk aversion on ship collision risk and sustainability assessment are investigated in this paper.

An approach to assess the risk associated with ship collision considering the risk attitude of the decision maker is presented herein. The probability of ship collision is calculated taking into account traffic data and operation condition. The consequences of collision are evaluated in terms of the environmental, social, and economic impacts associated with probabilistic damage conditions. The social, environmental, and economic metrics are evaluated separately and then social and environmental metrics are converted into an economic metric considering their associated monetary values. The consequences include downtime, fatalities, human injuries, oil spill, and economic loss. The economic loss, which is the sum of costs weighted by their probabilities of occurrence, includes repair costs, environmental losses, time loss costs, and costs of injuries and fatalities. Epistemic and aleatory uncertainties associated with both the damage states and consequences are incorporated in this methodology. The risk attitude of the decision maker is integrated within risk analysis by using utility function. The expected utility values associated with the ship collision risk are also investigated considering different risk attitudes. The approach is illustrated on a maritime transportation system located within the Delaware River region considering ship collision risk and sustainability. Ultimately, this approach can help the decision maker to make risk-informed choices considering risk attitudes.

2. Ship collision risk and sustainability assessment using utility theory

Quantitative risk assessment associated with waterways has received growing attention and is of vital importance to the safe navigation of ships. Marine traffic has increased significantly in the last few decades; consequently, the risk associated with maritime traffic has increased. This has led to high accident risk. This paper aims to assess risk due to ship collision by formulating a procedure to compute collision risk and sustainability in a probabilistic manner considering risk attitudes. The methodology for risk and sustainability-informed decision making under extreme events is illustrated in Fig. 1. The first step for risk-informed decision making is to identify the risk of structural systems under extreme events including natural and man-made hazards.

Risk is defined as the product of consequences of an unwanted event and its probability of occurrence. Risk-based assessment of ships under construction process and operation condition has been recently developed [16,17]. The quantitative risk assessment consists of three main parts: hazard exposure, structural vulnerability analysis, and consequences analysis [18]. The hazard exposure procedure determines the probability of occurrence of an extreme event. The vulnerability analysis is based on the condition states of the structural systems as well as collision scenarios; each structural damage condition is associated with specific consequences. A general formulation of risk R was provided by Ellingwood [19]

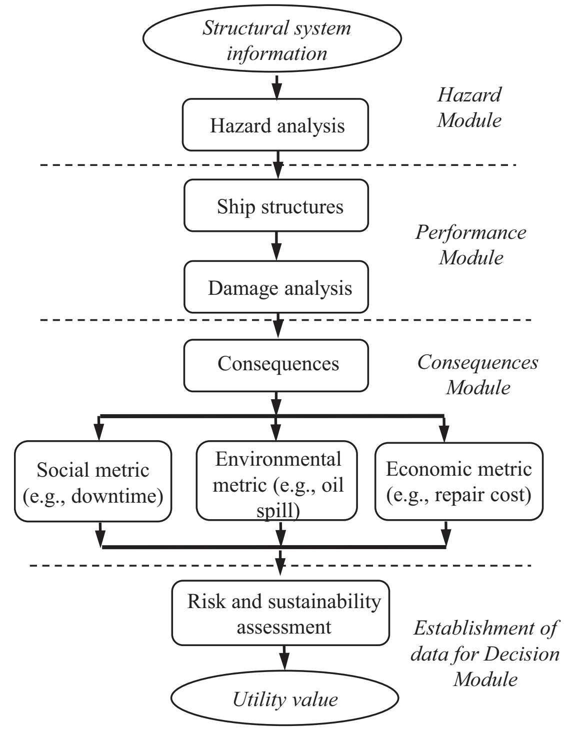

Fig. 1. The methodology for risk and sustainability assessment considering risk attitudes in terms of utility value.

$$R = P(H) \cdot \sum_{DS} C(Cons|DS) \cdot P(DS|H) \tag{1}$$

where $P(H)$ is the annual rate of occurrence of the extreme event H; $C(Cons|DS)$ is the conditional consequence (e.g., economic, social, and environmental) associated with a given damage state DS (e.g., minor, moderate, major, complete); and $P(DS|H)$ is the conditional probability of damage state given the extreme event H. Based on the theorem of total probability, the total risk is the sum of consequences weighted by the probability of experiencing these consequences associated with different damage states. To clarify this issue, the sample space of all possible damage states and associated consequences is illustrated in Fig. 2. There have been several research efforts focused on the ship collision probability [7,20,21]. However, more research is needed for ship probabilistic damage

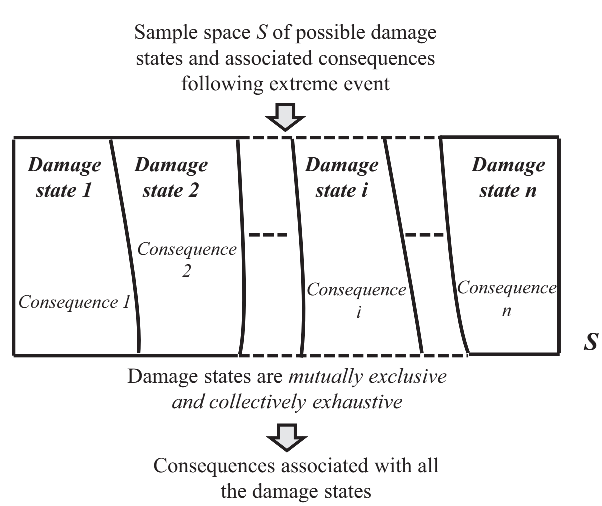

Fig. 2. Damage states and associated consequences.