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Port management and multiple-criteria decision making under uncertainty

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ABSTRACT

The methodology for port management in this study takes into account the stochastic nature of climate as well as of use and exploitation agents. It provides a probabilistic characterization of the performance of different alternatives in terms of a set of indicators that reflect the potential benefits for different interest groups. The joint distribution functions thus obtained for a set of pre-defined management alternatives are used to compare strategies and to make decisions, based on stochastic multi-criteria analysis. This method, which also addresses the uncertainty of decision-maker preferences, ranked the strategies, and at the same time, specified the typical decision-maker preferences for each strategy. In the analysis of a hypothetical port, four alternatives were designed as solutions for port congestion. The criteria selected were the service quality provided to vessels, the total goods handled and the profits accrued by the Port Authority. The criteria measuring the performance of each strategy were statistically analyzed first. Then, assuming the uniform distribution of decision-maker preferences, the alternatives were ranked, and the relative importance of each criterion in the decision-making process was obtained.

1. Introduction

Ports are basic elements in transport chains, especially for international trade. For example, ports handle 60% of Spain's exports and 85% of its imports. This amounts to 53% of Spain's trade with the EU and 96% of its trade with the rest of the world (Puertos del Estado, 2014). Ports are also excellent sites for factories that transform goods and thus increase their value. Furthermore, since they also host companies that provide all necessary services, ports have become important production centers that generate wealth and employment.

Since national governments are usually the owners of large ports, they are naturally aware of the impact of these facilities on the economy. Authorities thus foment port activity by implementing local, national, and international measures for this purpose. The Spanish State Ports and Merchant Marine Act (Royal Decree 2/2011) fosters the competitiveness of public ports to improve their performance and efficiency. In this context, the service level of a port is a crucial factor in building customer loyalty and attracting new trade routes.

From a management perspective, any action that enhances the performance of a port will almost certainly require large investments by the harbor authority or the licensed service companies. Given the stochastic nature of climate agents as well as of use and exploitation agents, the response of the system is random rather than deterministic. In this context an *agent* refers to any entity that can act or significantly affect the port system. Since investors must take certain risks, predictions of the effect that a management strategy will have on port operation should be accompanied by an assessment of the uncertainty involved.

Port management strategies are usually designed to achieve the management target. Given that a certain strategy may benefit or harm the interests of different groups of stakeholders, decisions should be transparent and based on sound criteria. An additional inconvenience is that it is often impossible to be aware of decision-maker preferences (Lahdelma et al., 2000). In such circumstances, stochastic multi-criteria acceptability analysis (SMAA) can be used to facilitate the decision-making process (see Tervonen and Figueira, 2008 for a survey).

There has been a considerable amount of research that has focused on effective ways of finding optimal solutions for hypothetical port management problems by taking into account the uncertainty of use and exploitation agents. For example, Özgüven et al. (2013) optimized the quay length by using a stochastic knapsack model. The revision in Bierwirth and Meisel (2010) surveyed work on berth allocation and quay crane scheduling problems. In a more general sense, the *Spanish Recommendations for Maritime Works* ROM 2.0 (Puertos del Estado,

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2012) incorporates the analysis of uncertainty in the design of mooring lines.

For a port system, in theory, it is possible to formulate a stochastic optimization problem where the objective function is a utility function defined in terms of several decision variables. As pointed out by Solari et al. (2010), the resolution of this type of problem with numerical techniques requires the evaluation of a relatively large number of alternatives, which in practice, is not viable except in the case of very simple harbor systems.

The most practical way of dealing with the overall complexity of port management is to simulate port operations. A case in point is Thiers and Janssens (1998), who used a discrete-event simulation model to assess the impact of the construction of a container quay on ship traffic in the port of Antwerp. Mazza (2001) optimized the number of quay cranes in a container terminal with a queuing network model also based on discrete-event simulation techniques. van Asperen et al. (2003) studied the influence of ship arrivals patterns on loading and unloading processes.

Simulation-based models have also been used to evaluate management alternatives. Demirci (2003) detected the bottlenecks in the port of Trabzon (Turkey) and assessed various investment alternatives. Huang et al. (2012) evaluated berth allocation policies for container ships in a port with different container terminals and proposed new strategies. However, none of this previous work has considered climate agents. Solari et al. (2010) proposed a risk-based methodology to optimize the design of navigation areas in a port. In their study, simulation techniques were used to obtain realizations of the climate agents and ship arrivals.

In reference to decision-making, the uncertainty inherent in criteria and the preferences of decision makers has been addressed in different ways. Chen (2001) implemented a fuzzy approach to select the location of a distribution center. In this research, triangular fuzzy numbers were used to model the lack of precise information concerning weights and criteria. Fuzzy logic is also used by Yeo et al. (2014), who proposed a port choice method with uncertain and incomplete information about ports evaluation.

Stochastic multi-criteria methods have also been used to solve environmental management decision-making problems (Hokkanen et al., 2000; Lahdelma et al., 2002; Félix et al., 2012). Regarding port planning and management, Hokkanen et al. (1999) used an SMAA method as a decision model for the planning of a new port in Helsinki. In their work, expert opinions characterized the uncertainty implicit in the potential benefits or adverse effects of the alternatives proposed.

This paper presents a methodology for port management and multi-criteria decision-making based on Félix et al. (2012). It allows stakeholders to select a certain management strategy from a pre-defined set of alternatives by taking into account the stochastic nature of the forcing agents (i.e. climate agents as well as use and exploitation agents). It uses simulation techniques to obtain realizations of the random processes that characterize these forcing agents and then estimates the response to each strategy by applying a model that simulates port operations.

The port simulation model takes into account the availability of berths and services and also the stoppage of activities due to severe climate conditions. The performance of the alternatives is characterized by the corresponding joint distribution function of a set of indicators that measure the benefits for different interest groups. These indicators are the following: (i) profits accrued by the Port Authority; (ii) total amount of goods handled; and (iii) level of service offered at the port. This information is then analyzed with a stochastic multi-criteria decision method SMAA-2 (Lahdelma and Salminen, 2001) that ranks strategies, and at the same time, calculates the relative importance of each criterion in the decision-making process.

This method was applied to a hypothetical congested port. The study proposes a set of alternatives aimed at improving the service level of the port and at increasing the traffic of goods. The three alternatives were A_1, A_2, and A_3, which envisaged different enlargements of the berthing line. Also considered was the zero alternative, A_0, in which no action is taken, and which is used as a reference value.

The main contributions of this work are (1) the implementation of a simulation model of port operations for a set of time series (realizations) of the random processes that characterize climate agents and use and exploitation agents; (2) the use of advanced simulation techniques (Solari et al., 2011; Solari and Losada, 2012) to obtain a large number of realizations of the multivariate random processes that characterize climate agents as well as use and exploitation agents to force the model; (3) the assessment of the uncertainty of port performance, inherited from forcing agents; and (4) the application of a stochastic multi-criteria method that effectively considers random criteria and the unknown preferences of decision-makers.

Section 2 of this paper outlines the methodology; Section 3 applies it to a hypothetical port after a description of the port configuration and the management problem. Also defined in this section are the strategies and the procedure followed to evaluate the performance of the strategies. Section 4 analyzes the results obtained from the risk analysis and the application of the SMAA. Finally, Section 5 presents the conclusions derived from this research.

2. Stochastic multi-criteria acceptability analysis for port management

This paper proposes a methodology for port management and decision making under uncertainty. The first step involves the evaluation of port operations conducive to the definition of the management targets to be achieved during a given time period, D_t. Various strategies, $A_1, A_2, \ldots, A_M$, are then designed to reach those targets. A set of indicators ξ_1 , ξ_2, …, ξ_N are also selected to measure the degree of fulfillment of the objectives and potential additional benefits and/or adverse effects (e.g. revenues and level of service).

The design of the alternatives should be based on an in-depth knowledge of the following: (1) the port configuration and its operations and (2) the potential actions that can be implemented to enhance its performance. Because of legal requirements as well as other constraints and also because of the availability of space and funds, the number of viable alternatives can usually be reduced to a small set. Their definition is site-specific and general criteria cannot be provided.

2.1. Assessment of uncertainty in the performance of a strategy

The performance of strategy A_m depends on port configuration (port facilities and services) and the forcing agents. These agents can be characterized in terms of a series of random processes (RPs): $X_1(t), \ldots, X_F(t)$, where t denotes time. The climate agents to be considered are those defined by significant wave height, mean wave period, mean wind speed, etc. Use and exploitation agents include sequence of ship arrivals, service times, and other factors.

Multivariate simulation techniques are employed to obtain random realizations, $x_1(t), \ldots, x_F(t)$, of these RPs. These time series are discretized into a sequence of states, where a state is defined as a period in which the agents can be assumed to be statistically stationary.

The response of the system to a given set of realizations of the random processes can be reproduced with a port model that sequentially simulates port activity during each state. The performance of the strategy for that realization is then quantified by the values of the selected indicators $\xi_1^{A_m}, \xi_2^{A_m}, \ldots, \xi_N^{A_m}$.