Dynamic programming algorithms for selection of waste disposal ports in cruise shipping

Shuaian Wang [a,b], Lu Zhen [c,*], Dan Zhuge [b]

[a] *The Hong Kong Polytechnic University Shenzhen Research Institute, Nanshan District, Shenzhen, China*
[b] *Department of Logistics & Maritime Studies, The Hong Kong Polytechnic University, Hung Hom, Hong Kong*
[c] *School of Management, Shanghai University, Shang Da Road 99, Shanghai 200444, China*

A B S T R A C T

The cruise industry has maintained a steady growth in the past 20 years. Due to the large number of cruise passengers and regulations on sea environment protection, determining at which ports to dispose of the waste generated onboard a cruise ship is a key decision to reduce the cost for a cruise company. We address four versions of the problem: the cruise itinerary is either static or dynamic and the amount of waste generated on each voyage leg is either deterministic or stochastic. We propose a polynomial-time solution algorithm for the static deterministic model, and the idea of the algorithm can also be used to solve the static stochastic model and the dynamic deterministic model. Second, we identify the structure of the optimal policy to the dynamic stochastic problem, based on which an efficient dynamic programming algorithm is developed. Extensive numerical experiments derived from problems of real-case scales demonstrate the efficiency of the proposed algorithms.

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1. Introduction

The cruise industry provides a package of recreational activities to passengers. On-board activities include casino gaming, gift shop sales, entertainment arcades, art auctions, photo sales, spa services, bingo games and lottery tickets, enhanced dining experiences in alternative restaurants, video diaries, golf lessons, and snorkel equipment rentals. Moreover, cruise ships will stay at several ports, which are often in different countries, and passengers can have a tour in the port cities. The cruising industry has maintained a steady increase in supply for the past 20 years. In 2014, the world cruise fleet had 296 ships (Cruise Ship Statistics, 2015), the number of cruise passengers reached a total of 22.04 million, and the global cruise industry generated revenues of 37.1 billion U.S. dollars (Cruise Industry, 2015).

A large cruise ship carries over 6000 passengers and 1500 crew members, and therefore the amount of waste generated by a cruise ship is also considerable. This significantly contrasts cargo ships, e.g., bulk ships (Magirou et al., 2015) and container ships (Bell et al., 2013; Psaraftis and Kontovas, 2013, 2014; Ng, 2015), which are usually manned with fewer than 30 crew members. There are mainly five waste streams from cruise ships: sewage, graywater, oily bilge water, solid waste, and hazardous waste (EPA, 2008). Sewage from cruise ships, also known as "black water", generally means human body wastes. Graywater generally means wastewater from sinks, baths, showers, laundry, and galleys. Oily bilge water is the mixture of water, oily fluids and lubricants from the machinery spaces of a cruise ship. Solid waste is the food waste, garbage, refuse, sludge, rubbish, trash, and other discarded materials. Hazardous waste is a type of waste containing hazardous instances. As

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reported by EPA (2008), every day a large cruise ship may generate 74,000 gallons of sewage, 249,000 gallons of grey water, 5300 gallons of bilge water, 50 ton of garbage, 12,000 bottles and 12,000 cans, and 10 tons of hazardous waste. Different waste streams are treated differently. Some waste must be off-loaded to shore reception facilities at ports for recycling or disposal, for instance, synthetic ropes, plastic bags, some solid waste that cannot be incinerated, a proportion of oily bilge water, and hazardous waste. Annexes V and VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) of the International Maritime Organization (IMO) have regulated the types of wastes that can be discharged into the sea and have imposed ships to provide facilities for the reception of waste. Most cruise lines have implemented environmental management systems to reduce, select, and manage the waste generated onboard, in order to be in compliance to the MARPOL requirements (Pallis, 2015).

This paper considers the waste that must be landed to the shore reception facilities. A cruise ship has an environmental officer (EO) onboard, a crew member in charge of looking after the waste. The EO reports to the Chief Officer the amount of waste that is onboard and the Chief Officer reports to the shore-side headquarter to decide whether to discharge the waste at the next port of call or not. Cost is a major concern in the choice of waste discharge port. Different ports have quite different prices for waste discharging: some ports, e.g., ports in Cyprus, impose a fixed charge no matter whether a ship actually discharges waste or not (that is equivalent to not cost for waste discharging in the decision process), and other ports can charge up to several thousand dollars. Therefore, it is vital to decide at which ports to discharge waste is the most cost-effective. Given a cruise ship that visits a sequence of ports according to a pre-determined schedule and waste is generated continuously along the voyage and the waste holding tank has limited capacity, we study the problem of determining at which port to dispose of the generated waste so as to minimize the total cost. We identify special structures of the problem and develop dynamic programming based solution approaches to address the problem. Our numerical experiments show a cost reduction of 30% using the proposed methods relative to a greedy waste disposal heuristic.

1.1. Literature review

The topic of this study belongs to the area of maritime transportation; and there are many quantitative studies in this area (Zhen, 2016; Zhen et al., 2017). While there is few quantitative study related to cruise ships, especially the waste management on cruise ships. There are only some qualitative works on waste generated onboard cruise ships. Dixon and Hughes (2000) reviewed the current regulations on cruise ship waste management set by IMO, mainly the MARPOL regulations. They also discussed a typical design of waste management systems onboard cruise ships. Johnson (2002) categorized the environmental impacts of cruise tourism, including (i) infrastructure impacts such as ship construction, the creation of cruise passenger terminal facilities and berthing access requirements; (ii) operational impacts involving the use of energy and water and air quality pollution; (iii) distribution impacts associated with tourists' travel and the logistics of supplying a cruise liner with provisions; (iv) use impacts which comprise the cultural impact of wealthy tourists and overcrowding created by large numbers of visitors at one destination; and (v) waste impact. He explored the potential strategies that can be employed by cruise line operators and cruise tourism destinations to manage the impact. He concluded that although the industry was taking a number of belated positive steps, the decision-makers in cruise tourism destinations, such as cruise port operators and port city governments, should work closely with cruise lines to facilitate integrated waste management and sustainable development. Polglaze (2003) highlighted the importance of management of ships' food waste and summarized the estimated rates of food waste generation for merchant ships, passenger ships, and fishing ships, by different sources such as the US National Research Council and International Maritime Organization (IMO). He conducted a survey of six ships and the survey revealed a general upward trend in per capita waste generation rate as a function of crew size. Based on surveys undertaken in 2000 and 2002 regarding the availability of port reception facilities for ship waste in the North Sea area, Carpenter and Macgill (2005) found that most North Sea ports had sufficient reception facilities and already met the EU Directive on reception facilities for ship waste. Butt (2007) studied cruise ship's waste management status in Southampton and investigated the disposal options for ship generated waste and the impacts of the waste on ports. He recommended all cruise ships should pursue a waste reduction strategy and the ports should provide adequate recycling, reduction and re-use facilities for waste. Macpherson (2008) reviewed the environmental, economic and societal impacts of cruise ship tourism. He pointed out that sustainable tourism policies and effective management of the tourism could yield high returns with low risks. Using a life cycle assessment, Zuin et al. (2009) identified and quantified the environmental impacts caused by ships' waste management in the port of Koper, Slovenia. They argued that critical environmental issues are caused by carcinogens substance, inorganic emissions and heavy metals, while the recovery of ship-generated oils is beneficial to reduce the fossil fuel consumption. Klein (2011) measured the impact of cruise tourism with the focus on the perceptions of host communities. Challenges faced by government, communities and the cruise industry were identified and analyzed to give a direction on how tourism can grow in a sustainable and responsible way. Therefore, the existing literature mainly focuses on technological and legal aspect of waste management by cruise ships. To the best of our knowledge, there is no study focusing on how a cruise ship could choose ports to dispose of its waste in the most cost-effective manner.

Our work is also related to literature on dynamic programming applications. Dynamic programming has been applied in many areas, such as inventory management, revenue management, electric vehicle charging, traffic sensor deployment, appointment scheduling, and inbuilt solvers of some exact solution methods (Zhen et al., 2018). Berman and Larson (2001) formulated a stochastic dynamic programming model for a vehicle product-delivery problem in which the volume of product required by each customer on a route is random, which is similar with the randomness of the generated waste in this