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Design of a hydrogen supply chain with uncertainty

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ABSTRACT

The use of fuels with low environmental impact has been recently highlighted in the media. In this context, the use of hydrogen as a fuel has been considered an alternative with significant potential to integrate a more sustainable energy matrix. However, there is still no appropriate infrastructure available for its commercialization. This study proposes a methodology for designing a hydrogen supply chain while considering the inherent uncertainty associated with the demand for this fuel in the future. To represent the problem and evaluate investment alternatives for the logistic infrastructure, an optimization model is proposed based on two-stage stochastic mixed-integer programming. To obtain solutions from the proposed model, the sample average approximation (SAA) method is used to obtain statistically certified solutions from a reduced number of scenarios. The proposed methodology was applied to the design of Great Britain's liquid hydrogen supply chain using real data. The proposed framework was able to provide solutions with optimality gaps estimated to be below 1% within an acceptable computational time, demonstrating the adequacy of the developed methodology.

Introduction

The current population growth and the ever-increasing demand for energy have been driving efforts to replace current sources of energy by more efficient ones. More recently, there has been significant effort to foment the use of sustainable energy (i.e., energy sources that are economic, efficient and clean).

A major concern is the pollution produced by conventional cars, which has boosted the search for new technologies. In this context, there has been a great deal of attention directed towards the development of environmentally friendly cars (i.e., green cars). Currently, the most relevant choices for better engines are the electric; the hybrid, which combines two engines, electric and combustion; and those fuelled by biofuels or hydrogen fuel cells.

Hydrogen is one of the most efficient fuels in terms of energy-movement conversion. It is approximately 2.5 times more efficient than gasoline and can be obtained both from renewable sources, such as water or biomass, and from non-renewable ones, such as coal and hydrocarbon sources. In addition to being an efficient alternative as a climate change mitigation strategy, hydrogen is a sustainable way to diversify

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the energy matrix, while ensuring supply safety, given that it can be easily converted into electricity whenever it is required.

To use hydrogen as an energy source at a large scale, research and investments are still required to overcome technical, economic, environmental, and structural obstacles. Several pilot projects have been developed around the world, seeking to find ways to make the adoption of hydrogen as an energy source feasible. In 2012 at the World Hydrogen Energy Conference [1], the automakers Daimler AG, Honda, Hyundai, and Toyota confirmed their plans to start the production of hydrogen fuel cell cars in 2015.

To make the use of hydrogen in vehicles feasible, it is necessary to install new fuelling infrastructure. However, because hydrogen is not yet common in the current market, it is difficult to scale the capacity of the network that would be required to supply future demand currently. These aspects imply a high level of uncertainty regarding the design and planning of a future logistic network. Combining this high level of demand uncertainty with management activities and physical distribution, the supply chain effectively has a network structure with complex relations among several agents that comprise several activities; therefore, the use of tools such as optimization models becomes necessary to support the decision-making process.

The hydrogen supply chain is composed of four different nodes: raw material suppliers (local or international); production plants; storage points; and refuelling stations. These nodes can be connected by different transport modes. The supplier sends the raw material to the production plant. At the plant, the feedstock is transformed in the final product (liquid or gaseous hydrogen), which is then transported to the storage points or directly to the refuelling stations. From storage, the product is sent to the refuelling stations whenever required. It is also possible to have product transportation between storage points, if its demand does not meet the projections at different places.

Previous studies have investigated this problem [2]. Given the complexity of this problem, several analytical overviews of the supply chain have been performed. However, they have not included the use of mathematical tools [3–6]. Additionally, simulation and dynamic programing tools have been used to obtain feasible solutions to the problem and manage the economic, financial and safety aspects of the network [7–9]. Many studies have attempted to evaluate the problem following a mixed-integer linear programming approach; some have used deterministic models [10,11], while others used multi-objective models [12–14].

One of the primary concerns when working with a mathematical model is to precisely determine the required detail level. The model must reflect the reality of the problem under consideration so that the solutions calculated by such model are consistent and applicable in practice. Conversely, a certain level of simplification must be used to ensure that solutions can be found within reasonable computational times.

A similar tradeoff is inherent to uncertainty-related aspects into optimization-based models. Typically, input data uncertainty is represented by discrete scenarios (and their occurrence probability), and those are considered all at once in the optimization process. However, to accurately represent high levels of uncertainty (i.e., large number of elements subject to uncertainty and their correlations) a large number of such discrete scenarios might be necessary, which jeopardizes computational tractability due to solving large scale models (i.e., models with large numbers of variables and constraints).

Despite challenging computational aspects, Shapiro and Philpott [15] show that a two-stage stochastic model provides significant advantages to problems regarding the infrastructure supply-chain dimension. Kim et al. [16] was one of the first stochastic approaches to manage the uncertainty in demand but neglected the evolution of the network over long-term future planning. Almansoori and Shah [17] try to manage the evolution of the network, but the resulting complexity produced long computation times. Dayhim et al. [18] considered constraints and the costs of ecology, energy and risks to the economic model. All of these previous works were only able to manage a small number of scenarios. Until recently, the maximum number of scenarios used in the models was 10 [18]; that is a problem in the hydrogen supply chain subject because the demand is particularly difficult to anticipate.

This study presents several contributions to the current literature on the hydrogen supply chain design problem. The objective is to develop a generic methodology for the design and planning of the hydrogen supply chain problem with demand uncertainty that can manage a very large number of demand scenarios efficiently, so a more realistic approach (i.e, with larger volume of data) can be considered into the assessment. To reach this objective, a two-stage stochastic mixed-integer optimization model, based on previous studies of Almansoori and Shah [20] and Dayhim et al. [18], is proposed to represent the logistic infrastructure, considering uncertainty in the demand forecast and seeking to evaluate different investment alternatives.

The sample average approximation (SAA) is applied to the stochastic model, which allows the consideration of uncertainty in a broader perspective and provides statistical certificates on the solution quality [19]. That allows the stochastic process that will model future hydrogen demands. No previous work has approached this problem proposing this methods combination. The proposed methodology was applied to a real-world case study in the design of Great Britain's liquid hydrogen supply chain serve both to validate the framework and to further extend the research on this problem type.

Problem description

Four types of agents are present in the hydrogen supply chain: raw material suppliers (national or international); production plants; storage points; and fuel stations. Different arcs that represent distinct transportation modes connect these agents. The product delivery, which is defined by the physical state of the hydrogen (i.e., solid, liquid or gaseous), will determine which transportation mode must be used. The decision concerning the physical state in which the hydrogen will be transported is critical for determining investment and operational costs, which impacts location decisions and transportation mode selection.