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Integration of interpretive structural modelling with Bayesian network for biodiesel performance analysis

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ABSTRACT

The performance of a biodiesel system can be affected by varied risk factors. The numbers of such risk factors are large and their interdependencies are vague and complex. The purpose of this study is to define relationships among such risk factors and integrate them with an objective risk analysis approach. In the present study, an interpretive structural modelling (ISM) approach was used to identify relationships among risk factors while a Bayesian Network (BN) approach was employed to define the strength of dependence and conduct a risk analysis. The results indicate that among 25 risk factors, operational safety is a key biodiesel performance factor. The analysis also highlights that the impacts of occupational health and natural resources depletion are strongly dependent on environmental parameters. Occupational health is also strongly dependent on plant safety. The results show that the interdependency between occupational health and natural resources depletion is weak.

1. Introduction

With population growth, the demand for energy, and particularly fossil fuels, is on the rise. This growing demand to consume fossil fuels has led scientists to explore innovative technologies to produce alternate energy resources. Of potential alternative energy sources, biodiesel seems to be a promising one. Biodiesel, which is produced by a transesterification reaction, has been produced using various new methods and alternate raw materials [1–7]. Technological innovations in biodiesel production processes have also introduced various uncertainties. In terms of performance, there are various risk categories, which could be characterized to study biodiesel performance risk factors. The nature of the interdependencies of such risk factors has not been studied to date. A well-developed biodiesel performance risk management system requires the identification of biodiesel performance factors as the first step. However, identification of such factors and their quantitative dependency is quite vague and no research has been done in this area.

This paper aims to analyse the risk factors affecting biodiesel production and their use, henceforth referred to as a biodiesel performance system. The interdependencies of biodiesel production and use were studied by implementing interpretive structural modelling (ISM). A Bayesian Network (BN) approach was integrated with ISM to identify the strength of such interdependencies and to conduct a risk analysis. A brief review of the applications of ISM in engineering analysis is presented below.

Warfield [8] proposed interpretive structural modelling (ISM) which was used to develop a visual hierarchical structure of complex systems. The technique was used in managing decision-making for complex problems. The input for the ISM technique was unstructured and used unclear information about the system variables and their interdependencies. The output of ISM analysis was a well-defined, classified and informative model, which is useful for many other purposes.

Pfohl et al. [9] implemented ISM to study the interdependencies in supply chain risks. The interrelationship among supply risk factors, they developed, was based on the dependence and driving power of respective factors. Their study was helpful to supply chain risk managers making decisions about resources management. They studied 21 risk factors and initial interrelationships were developed using group discussions among the authors and fellow researchers.

Singh et al. [10] structured nine barriers in knowledge management (KM) in business strategy. The KM barriers were those, which adversely affect the implementation of KM in a business

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organization. They implemented ISM methodology for their studies. The mutual relationships among different barriers were classified in different levels and included a visual correlation as well. However, the study was lacking in explaining how weak or strong relations were among various interconnected factors.

Wang et al. [11] have utilized this methodology to determine the correlations of risk factors in an Energy Performance Contracting (EPC) project. The applications of ISM to their EPC project resulted in a five-level hierarchical model using EPC project risk factors. There were 25 risk factors that were studied to develop a visual correlation, categorised in five levels. The study helped stakeholders to manage surface, middle and deep risk factors that affect an EPC project.

ISM has found its applications in various other fields of studies including financial decision making, complex engineering problems, total productive maintenance (TPM), competitive analysis and electronic commerce [12–15]. However, implementation of ISM for a process system has been less studied. As is evident, most previous studies have implemented ISM to study the qualitative relationships among different factors. Nevertheless, only a few of those studies have developed a quantitative relation among those factors. Since the development of a qualitative relationship does not predict whether the relationship is weak or strong, there is a need to develop a model, which shows such strength relations. Until today, biodiesel production systems have been much studied from their economic and environmental aspects. For example, there have been various studies on biodiesel process economics [16–19] and the related environmental impacts [20–23]. These studies have considered the economic and environmental aspects of a biodiesel production system using new and different raw materials and production technologies. However, these studies have not considered the performance of the biodiesel production system. Since the production of biodiesel is affected by various performance risk factors, considering only economic and environmental impacts made such studies vague and do not represent a complete picture of a biodiesel production system. Moreover, previous studies do not consider ways to better maintain the performance of a biodiesel system.

As mentioned earlier, this study integrates ISM and BN to conduct a biodiesel system performance risk analysis. The study considers biodiesel performance in three dimensions: i) process, ii) design and installation and iii) operations. This study is helpful to analyse biodiesel performance throughout the process life cycle. It assists in identifying bottlenecks throughout the life cycle of biodiesel and factors affecting these bottlenecks. Swift actions can be taken to overcome bottlenecks to bring biodiesel closer to being a green, safe and economic alternative fuel.

2. Problem definition

A biodiesel life cycle and economics study relies on various biodiesel performance risk factors. These risk factors are widespread in various performance dimensions and only a vague picture of their hierarchical order is present, which indicates that the impact of one risk factor on others or over a whole network is quite ambiguous. Therefore, there is a need to develop a qualitative as well as quantitative relationship among such risk factors. The qualitative relationship provides the interdependencies among various risk factors and quantitative analysis provides the strength among those risk factors. In order to perform such an analysis, three dimensions of biodiesel performance are included in this study, namely process, design and installation and operations. This study does not include technological modifications in vehicles or infrastructure for the use of biodiesel as fuel or the performance of biodiesel blends with diesel fuels. The stages of process performance under the study are technological maturity, size and complexity, organizational support, costs, benefits, environmental impacts, safety and risk management. In terms of design and installation, the various stages under study are regulatory, technical and financial compliance. Also under study are suppliers, intellectual property rights and organizational and strategic components. The stages of operational performance include environmental, health and safety risks, flexibility, engineering features, reliability, operational effectiveness, technological innovation and profitability. The input data for this study were the development of the binary contextual relationships among risk factors, using experts' opinions. The experts were a research group of a senior University professor, who has an extensive knowledge and a broad experience in process engineering research and development. Various risk factors for process, design and installation and operations categories are shown in Tables 1–3 respectively. The main objective of this article is to investigate interdependency of various biodiesel performance risk factors and to study the quantitative strength of their relationships using conditional and marginal probabilities. Due to space limitations, the application of the methodology developed for all risk factors is not possible. Hence, a case study of environmental, health and safety risk for operations is chosen to demonstrate methodology. The risk category of environmental, health and safety risk consisted of five risk factors: environmental concerns, human health, occupational health, plant safety and natural resources.

3. The analysis methodology

This research was performed using a nine step approach. The work integrated ISM and BN approaches. ISM is an interpretive method which takes into account structural mapping of various risk factors [9]. In order to develop the mapping, the risk factors were first defined and then their order of complexity was studied. This provides the influence between the elements. The modelling converts a complex undefined (or badly defined) system into a well-presented and well-organised system, which consists of a directed graph called a digraph. The complex system developed as the digraph is known as a 'basic structural model', the expansion of which leads to an 'interpretive structural model'. The methodology takes into account a group discussion from experts on how the elements are related to each other. The analysis was further enhanced by developing a Bayesian network (BN) model. The BN model helps to quantify the strength of relationships rather than merely considering the qualitative relationships. The definition of strength used here refers to the strength of risk element *i*'s impact on the risk element *j*'s probability of occurrence. Since risk element *i* may or may not occur, the probability concept used is the conditional probability. The schematic flow of the methodology is shown in Fig. 1. The various steps in ISM modelling are as below.

Step 1: Risk factors identification

In this step, different risk factors were identified related to three categories of biodiesel performance study. Those three categories were 1) process 2) design and installation 3) operations. These categories were sub-categorised using the research/work from previous studies [24–31].

Step 2: Development of contextual relation among variables

In this step, a contextual relationship was developed among the variables identified in step 1. This relationship could be neutral, influential or comparative in nature. A pair-wise relation was studied. If a relation existed between two variables, it was written