5-2-2019

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Niamat Ullah Ibne Hossain
Mississippi State University

Farjana Nur
Mississippi State University

Raed Jaradat
University of Southern Mississippi

Seyedmohsen Hosseini
University of Southern Mississippi, mohsen.hosseini@usm.edu

Mohammad Marufuzzaman
Mississippi State University

See next page for additional authors

Hindawi
Complexity
Volume 2019, Article ID 3518705, 17 pages
https://doi.org/10.1155/2019/3518705

Research Article

Metrics for Assessing Overall Performance of Inland Waterway Ports: A Bayesian Network Based Approach

Niamat Ullah Ibne Hossain,[1] Farjana Nur,[1] Raed Jaradat,[1] Seyedmohsen Hosseini ,[2] Mohammad Marufuzzaman,[1] Stephen M. Puryear,[3] and Randy K. Buchanan[4]

[1]*Department of Industrial and Systems Engineering, Mississippi State University, P.O. Box 9542, Mississippi State, MS 39762, USA*
[2]*Industrial Engineering Technology, University of Southern Mississippi, Long Beach, MS 39560, USA*
[3]*Center for Advanced Vehicular Systems Extension (CAVSE), Mississippi State University, 153 Mississippi Parkway, Canton, MS 39046, USA*
[4]*Institute of Systems Engineering Research (ISER), U.S. Army Engineer Research Development Center (ERDC), 3909 Halls Ferry Rd, Vicksburg, MS 39180, USA*

Correspondence should be addressed to Seyedmohsen Hosseini; mohsen.hosseini@usm.edu

Received 4 December 2018; Accepted 31 March 2019; Published 2 May 2019

Academic Editor: Lucia Valentina Gambuzza

Because ports are considered to be the heart of the maritime transportation system, thereby assessing port performance is necessary for a nation's development and economic success. This study proposes a novel metric, namely, "*port performance index (PPI)*", to determine the overall performance and utilization of inland waterway ports based on six criteria, *port facility, port availability, port economics, port service, port connectivity, and port environment*. Unlike existing literature, which mainly ranks ports based on quantitative factors, this study utilizes a Bayesian Network (BN) model that focuses on both quantitative and qualitative factors to rank a port. The assessment of inland waterway port performance is further analyzed based on different advanced techniques such as sensitivity analysis and belief propagation. Insights drawn from the study show that all the six criteria are necessary to predict PPI. The study also showed that port service has the highest impact while port economics has the lowest impact among the six criteria on PPI for inland waterway ports.

1. Introduction

With the aid of technology, multiple transportation modes such as rail, water, road, and air are used to transfer goods from one destination to another in a timely fashion. Certain important goods, such as heavy load items or bulk cargos (e.g., ore, grains, and coal), machinery, bulk liquids and oils, automobiles, containers, and perishable refrigerated items require safe shipping to the desired destination. Research showed that ground or air transport is not recommended for these types of goods and the preferred transportation option is by maritime [1]. Maritime transportation is more economic, safe, and environmentally friendly.

Ports are mainstay on maritime transportation system as they play a major role in the global and domestic freight transportation. Ports are generally categorized into two major classes: *seaports* and *inland waterway ports.* Inland ports, known as coastal gateways for global trade, contribute to the rural, industrial, and agricultural development [2, 3]. Statistics show that 41 US states are being directly served by inland and intracoastal waterways for freight and passenger transportation. Inland waterway ports are located near a navigable river connected by a series of major canals and operated by lock and dam mechanism [4]. Unlike seaports, inland waterway ports do not have a deep draft; thus they cannot handle barges drafting more than 9 feet. Inland ports serve as a principal media for bulk transportation of the agriculture, mining, and manufacturing sectors with the connection of other intermodal facilities such as railroads and highways [3, 4]. A high number of current US ports are still underperforming due to the lack of proper management plans and decisive operational strategies [5]. To improve the overall ports' performance, port authorities should advance their operational strategies by integrating cutting-edge technologies and agile planning. Port performance measurement is quite complex, due to the different port activities ranging from economic to technical to environmental. The overall ports' performance can be assessed through calculations of various performance activities [6, 7].

Due to the rapid advancement of global supply chain, inland waterway transport has become one of the important transportation modes (Weigmans et al., 2014). Thus, there is a need to employ a more "systemic" approach to better understand and manage any kind of undesirable consequences emanated from this complex system [8–10]. A major issue germane to inland port is the selection of ports based on performance indicators where these indicators determine the ranking of ports. Over the last decade, many port-related researches including sea and inland waterway are conducted on performance management and site selection. For example, Wiegmans et al. (2014) conducted a detailed statistical analysis on the performance of the Dutch inland ports. They measured the performance of inland ports through transhipment level and growth in transhipment influenced by economic factors. Results indicated that the presence of a robust container terminal is necessary for a better port performance. Shetty and Dwarakish [7] identified a correlation between different port performance parameters such as loading/unloading rate, container dwell time, and terminal storage with overall productivity. The productivity is measured based on the number of vessels handled by the port. Along the same line, Kutin et al. [11] analyzed the relative efficiencies of fifty ASEAN ports and rank the ports efficiencies based on inland or sea type and supportive yard equipment. Alamoush [12] used a quantitative approach to study the impact of hinterland transport, specifically land transport (trucks) on the operational performance of the Jordanian inland port system. The findings from this study indicate that efficient hinterland transport system improves the operational performance of the inland waterway port. Oliveira and Cariou [13] developed a truncated regression model to explore the influence of interport competition on port efficacy and to investigate how the interrelationship between interport competition and efficacy can be varied if the assessment is performed at different geographic level. They suggested that interport competition has a reverse relationship with port efficacy and this negative relationship becomes more widespread when the competition occurs at a regional level compared to global levels. Bichou and Gray [14] proposed a conceptual framework of port performance through the lens of logistic and supply chain perspectives.

The current body of the literature is replete with other theoretical and empirical studies that focus on the subject of port performance and different types of port efficiencies. Interested readers can refer to the works of Coto-Millan et al. [15], Notteboom et al. [16], Barros [17], Díaz-Hernández et al. [18], Panayides et al. [19], Wanke [20], Chang and Tovar [21, 22], and Tovar and Wall [23]. Likewise, there are some analytical studies that have been devoted to other aspects pertaining to seaports, such as seaport characterization and classification (e.g., [24]), port operations and resilience (*e.g.*, [25–27]), port selection (e.g., [28–31]), and port competitiveness (e.g., [32, 33]). In this research we propose a unique set of determinants *(i) port facility, (ii) port availability, (iii) port economics (iv) port service, (v) port connectivity, and (vi) port environment* that impact the inland port performance. These determinants were derived based on Minimum Link Set (MLS) perspective. A MLS is a minimum set of operational factor or component required for the system to actively perform (Johansen and Tien; 2017), which implies failure of any factor or component within a system triggers cascading impact and leads to failure of the MLS (Jianag et al., 2016). Table 1 provides a summary of the current themes related to the different aspects of port literature. These themes serve as a baseline in the development of the proposed model.

Although there are many theoretical and empirical studies focused on the analysis and characterization of seaports, there is scant research that has attempted to quantify the performance of inland port using unique set of determinants. To address this gap, the following are the contributions made by this research:

(i) Propose a new metric "*port performance indicator (PPI)"* to assess the probability of an inland port performance.

(ii) Propose a probabilistic graphical model, a Bayesian network (BN), to predict the probability of port performance based on six criteria.

(iii) Conduct different types of analysis such as belief propagation and sensitivity analyses to provide better insights regarding the results of the proposed model.

(iv) Use BN as an effective tool in solving transportation and logistics management problems.

To the best of our knowledge, this is the first attempt to assess the probability of inland port performance using a Bayesian approach (BN). This research also presents the efficacy of BN tool in the context of transportation and logistics management. BN has some advantages over other approaches. BN is a powerful analytical tool that can be used for decision-making under uncertainty. Another important feature of BN is the ability to model both qualitative and quantitative variables which is different from other approaches such as swing weight, Analytical Hierarchy Process (AHP), or Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). BN can also be used to conduct probabilistic scenario analysis known as *belief propagation analysis*. BN accounts for all causal factors to produce a final model, to reduce the burden of parameter acquisition, and to overturn the previous assumption by taking new evidences into consideration such as *subjective belief* and *objective data* [34]. The Bayesian approach has been used in different domains and applications such as electrical infrastructure system [35], security management [36], customer service management [37], traffic accidents [38], manufacturing systems [39], natural resource management [40, 41], power system [42], and data classification [43], electric vehicle [44], and supply chain and logistics [45, 46].

An overview of BN is presented below, followed by the identification of the criteria and subcriteria that impact the

Table 1: Current themes of the port literature.

Authors	Measures for port	Approach
Wiegmans et al. (2015)	Inland port performance	Statistical (regression) analysis
Shetty and Dwarakish [7]	Inland port performance and productivity	Statistical analysis
Kutin et al. [11]	Relative efficiencies	Data Envelopment Analysis (DEA)
Alamoush [12]	Port operational performance	Conceptual framework with analytical model
Oliveira and Cariou [13]	Port efficiency	Data Envelopment Analysis (DEA)
Bichou and Gray [14]	Port performance	Conceptual logistic and supply chain approach
Coto-Millan et al. [15]	Port economic efficiency	Stochastic Cost Frontier (SCF)
Notteboom et al. [16]	Relative efficiency of container terminal	Stochastic Cost Frontier (SCF)
Baros [17]	Technical efficiency	Stochastic Cost Frontier (SCF)
Díaz-Hernández et al. [18]	Technical and allocative efficiency	Stochastic Cost Frontier (SCF)
Panayides et al. [19]	Economic efficiency	Data Envelopment Analysis (DEA)
Wanke [20]	Physical infrastructure efficiency, shipment consolidation efficiency	Data Envelopment Analysis (DEA)
Chang and Tovar [21, 22]	Technical efficiency	Stochastic Distance Function (SDF)
Tovar and Wall [23]	Port productive efficiency	Directional technology distance function approach
Bichou and Gray [24]	Terminology for classifying seaport	Conceptual framework
Hosseini and Barker [25, 26]	Resilience	Bayesian approach
Sierra et al. [27]	Harbour operability	Numerical Model
Ugboma et al. [28]	Port selection	Analytical Hierarchy Process (AHP)
Chang et al. [29]	Port selection factor	Exploratory factor and confirmatory factor analyses
Gohomene (2008)	Port selection	Analytical Hierarchy Process (AHP)
Nur et al. [31]	Port selection	Stochastic Analytical Hierarchy Process (SAHP)
Song and Yeo [32]	Competitiveness of container ports	Analytical Hierarchy Process (AHP)
Yeo et al. [33]	Competitiveness of container ports	Fuzzy methodology

overall inland port performance and translate these criteria into BN model to assess the probability of PPI. From this, belief propagation and sensitivity analyses are presented, respectively. The paper concludes with implications, recommendations, and future research.

2. Fundamentals of Bayesian Network

BN is a Directed Acyclic Graph (DAG) which consists of vertices (nodes) and edges (arcs) where vertices represent the variables and edges signify the relationship between the two variables in the existing network. BNs are structured based on Bayes' theorem, capable of making statistical inferences in a rational way by updating the prior beliefs of any event which means entering an evidence in an *child node* will lead to backward belief propagation and ultimately result in updating the probability distributions for the *parent node(s)* and vice versa [34]. BN requires fewer probability parameters compared to a full joint probability model. Equation (1) represents the generic rule of the Bayesian theorem [47].

$$P_R(A_1, A_2, A_3 \ldots A_n) = \prod_{i=1}^{n} P_R(a_i \mid \mu_i) = \prod_{i=1}^{n} \phi_{A_i|\mu_i} \qquad (1)$$

In (1), the underlying network is specified by a pair R = $\{G, \Theta\}$ where G is the directed acyclic consisting of a set of random variables $A_1, A_2, A_3 \ldots A_n$, and Θ representing the set of the probability functions. Each a_i in A_i is provisioned on μ_i for the set of the parameters of A_i in G.

In the underlying structure of a BN, the initial probabilities (unconditional) or prior information of the root nodes can be obtained from a subjective judgment (e.g., expert knowledge /historical data) or through a frequentist approach (observed data). The conditional probabilities refer to the quantitative degree of belief to describe uncertainty among nodes. In some cases, it is challenging to define the conditional probability table (CPT) for a large set of data. Thus, we used *AgenaRisk* software to offset this challenge, having said that Bayesian equation is used to calculate CPT with known initial probabilities of each node as shown in (2) [48].

$$P(A_j \mid B) = \frac{P(B \mid A_j) \text{ x } P(A_j)}{P(B \mid A_i) \text{ x } P(A_i)} \qquad (2)$$

where $i = 1, 2, \ldots, n$; $j = 1, 2$.

To illustrate the operational principle of BN networks, let us consider a BN structure with a set of variables $R = \{A_1, A_2, A_3, A_4, A_5, A_6\}$ and a set of edges to show the conditional interdependencies among the variables (see

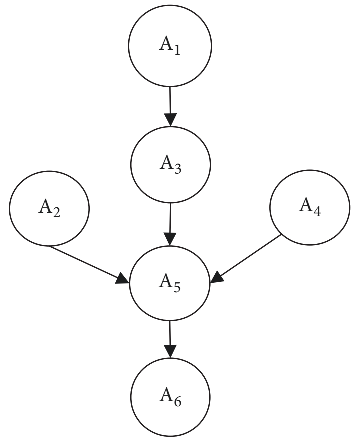

Figure 1: A sample of the Bayesian Network (BN) with six nodes.

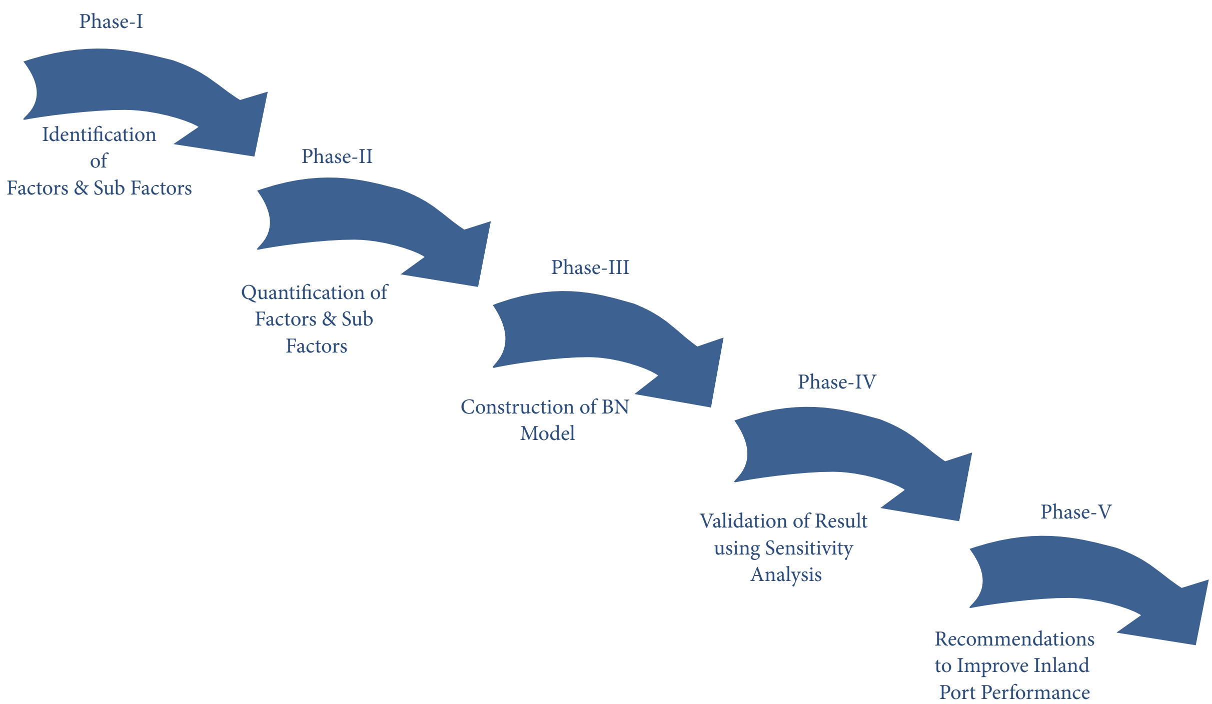

Figure 2: Proposed framework for inland port performance assessment.

Figure 1). The general expression of the full joint probability distribution can be represented as follows:

$$P(A_1, A_2, A_3, \dots A_n) = P(A_1 \mid A_2, A_3, \dots A_n) \cdot P(A_2 \mid A_3, \dots, A_n) \dots P(A_{n-1} \mid A_n) P(A_n) = \prod_{i=1}^{n} P(A_i \mid Parents(A_i)) \quad (3)$$

The corresponding decomposition of the joint distribution of variables can be streamlined as follows:

$$P(A_1, A_2, A_3 \dots A_6) = P(A_1) P(A_2) P(A_4) \cdot P(A_3 \mid A_1) P(A_5 \mid A_2, A_3, A_4) P(A_6 \mid A_5) A_4 \quad (4)$$

3. Proposed Framework for Inland Port Performance Assessment

The proposed framework consists of five phases as illustrated in Figure 2.

(i) *Phase I.* Identification of factors and subfactors: the first phase is to identify the factors and subfactors that could impact the performance of port infrastructure. First, the current research related to port performance is studied and analyzed, and initial subcriteria are constructed. Second, opinions from domain experts are incorporated into the scope of port performance management and the less important subcriteria are discarded, and finally all the subfactors are clustered

Table 2: Inland port performance index scale.

Intensity of PPI	Definition	Significance
PPI > 80%	High Standard	Maintains superior standard on all the performance criteria.
60% < PPI < 80%	Moderate Standard	Meets adequate performance standard, but the scope of improvement is available.
PPI < 60%	Low Standard	Performance level is lower than average and significant improvement is needed.

into six main criteria, namely, *(i) port facility, (ii) port availability, (iii) port economics, (iv) port service, (v) port connectivity, and (vi) port environment.*

(ii) *Phase II.* Quantification and assessment of factors and subfactors: the second phase is to quantify the factors and subfactors. It also includes the determination of the likelihood of the related factors based on the subjective or frequentist approach.

(iii) *Phase III.* Construction of BN model: a BN is used to quantify the probability of the port performance.

(iv) *Phase IV.* Analysis of result: different techniques such as sensitivity analysis and belief propagation analysis were conducted to draw the insights from Phase III.

(v) *Phase V.* Recommendation for port performance improvement: based on the analysis, different recommendations are provided to improve the overall port performance.

3.1. Performance Standard for Inland Waterway Port

3.1.1. Proposed Inland Port Performance Index (PPI). Based on existing literature, a number of interrelated factors that influence the performance of inland waterway ports are identified. This research summarized all the possible factors and classified them into six criteria: *(i) port facility, (ii) port availability, (iii) port economics, (iv) port service, (v) port connectivity, and (vi) port environment.* The proposed Inland Port Performance Index (PPI) describes the probability of the performance standard that an inland waterway port can meet. For instance, the probability of PPI being 80% true means that there is 80% likelihood that the specific port will meet the performance standard based on the cited criteria.

The characterization of PPI incorporates the most significant parameters that impact the performance standard of the inland waterway port. In order to express PPI through a numerical scale, a value between 0 and 100 is assigned. It is important to note that the selected metric is based on expert knowledge within inland waterway port system and is used to highlight the overall performance of an inland waterway port. The subjective description of the metric values of PPI is explained in Table 2 and the base model of the BN for measuring PPI is illustrated in Figure 3.

3.1.2. Port Facility (Criterion #1). An inland port is highly integrated with a maritime terminal to ensure smooth flow of logistical activities across the globe. Port terminal amenities and other key facilities such as warehouse area, outdoor ground storage, and dock-wall depth govern the overall facility of the inland port for freight handling and distribution.

(i) *Terminal facility*: it consists of three contributors port throughput, types of existing terminal, and number of diversified products.

(a) *Throughput*: it is volume of cargo or number of vessels that a port can handle over time. Throughput can be measured in terms of tons or transportation equivalent units (TEU). Different factors such as competition between ports, international and domestic cargo demand, and business arrangements can influence the terminal throughput [49].

(b) *Types of existing terminal*: from a transport facility viewpoint, a top-tier inland port possesses three kinds of terminals: *Satellite terminal* located near the port facility and used mainly for container trans-loading, *Freight distribution cluster or load center* dedicated to support warehousing and logistic functions, and *intermodal terminal* used to regulate freight circulation through intermodal facilities [50].

(c) *Number of diversified products*: based on United Nations Conference on Trade and Development (UNCTAD), five categories of seaborne trade that a port can handle are *containers, petroleum, crude oil, main bulk commodities, and other dry products*. However, for an inland port, diversity in the type of products handled is limited to two to three types.

(ii) *Key facilities*: warehouse area, outdoor ground storage, and dock-wall depth play a vital role in freight storage and port performance.

(a) *Warehouse area*: warehouse facility is tied up with freight storage and distribution operations. Sometimes warehouse areas are facilitated by staging areas to support loading and unloading operations.

(b) *Outdoor ground storage*: outdoor ground storage offers port expansion opportunity due to possible growth rate in port throughput. Some ports use outdoor ground storage as cargo staging/assembly zone, maintenance area, barge consolidation and deconsolidation facility, and container depot.

(c) *Dock-wall*: dock wall facilitates berthing area for vessel/cargo.

3.1.3. Modelling of Port Facility. In order to model port facility, three variables were used: *(i) Boolean variables* are

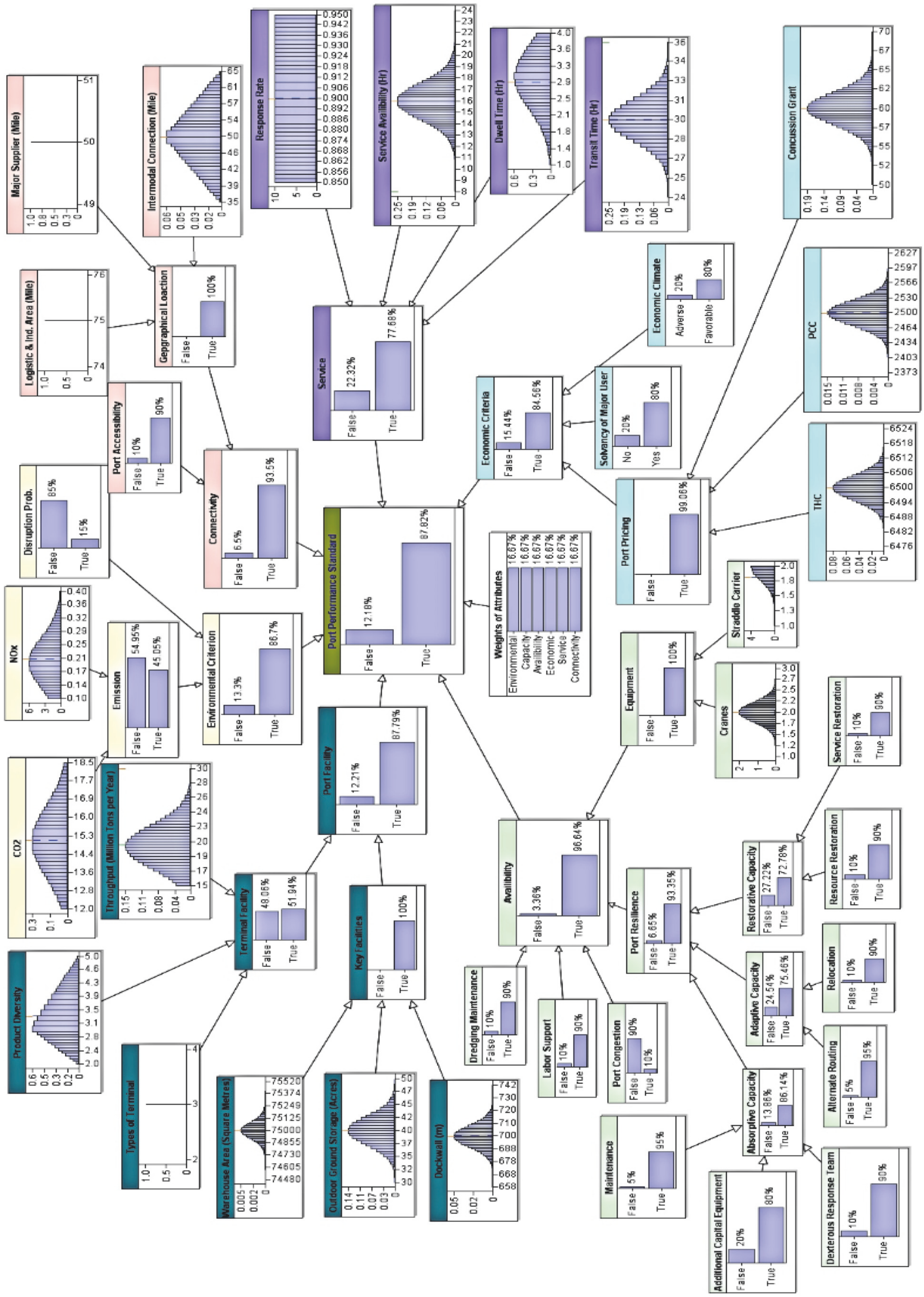

Figure 3: Base model of the Bayesian Network for measuring PPI of inland port.

expressed in forms of a dichotomous response (true/false, yes/no) to present positive and negative outcomes respectively, *(ii) fixed variables* are modelled in constant values, and *(iii) continuous variables* are random variables with a known probability distribution.

A Boolean variable with two states of *true* and *false* are used to model facility, terminal facility, and key facilities nodes. The true state represents a positive outcome while the false state indicates a negative outcome. For instance, in Figure 3 the probability of facility being true or likelihood of meeting port facility is 87.41% while the probability of facility being false is 12.58%. Similar logic is also applicable to the other two Boolean nodes (terminal facility and key facilities).

Truncated normal distribution is used to model continuous variables such as throughput, warehouse facility, outdoor ground storage, and dock-wall area. Truncated normal distribution is a simple modification of a normal distribution that confines the mean values between lower and upper bounds. For example, the area of the warehouse facility cannot be negative and maximum warehouse area for the inland port does not generally exceed 1,50000 m^2. Hence, the truncated normal distribution is found to be the most appropriate distribution to model the aforementioned continuous variables. The truncated distribution is defined in terms of four parameters: μ, mean (i.e., central tendency); σ^2, variance (i.e., confidence in the results); lower bound and upper bound.

It is apparent from Figure 3 that port facility is conditioned upon terminal facility and key facilities. There might be other hidden factors contributing to port facility. This can be better described by the NoisyOR function. These hidden or missing parameters are known as "leak parameters" in NoisyOR function (see (5)).

$$NoisyOR\ \left(A_1, S_1, A_2, S_2, \ldots A_n, S_n, l\right) \tag{5}$$

Leak factor (l) can be defined as the extent to which missing factors from the model can contribute to the consequence being true. It is the probability that B will be true when all of its causal factors are false. The conditional probability of B obtained with the NoisyOR function is presented below in (6).

$$\begin{aligned} P\left(B = True \mid A_1, A_2 \ldots A_n\right) &= 1 \\ &- \prod_{i=1}^{n} \left[\left(1 - P\left(B = True \mid A_i = True\right)\left(1 - P\left(l\right)\right)\right\}\right] \end{aligned} \tag{6}$$

The modelling procedure for port facility and its contributors are summarized in Table 3.

In the proposed BN model, in order to calculate the posterior probability of the "port facility", we used NoisyOR function, which is represented in (7). The equation means that, in order to meet port facility, both factor terminal facility and key facility are equally responsible (75%) and other hidden factors are contributing rest of 25% to achieve desired port facility.

$$\begin{aligned} Port\ Capacity = NoisyOR\ &\left(Terminal\ Facility, 0.75,\right. \\ &\left. Key\ Facility, 0.75, 0.25\right) \end{aligned} \tag{7}$$

3.1.4. Port Availability (Criterion #2). Availability is the level to which the system (port) can self-organize itself to avoid any discontinuity of the system's performance due to undesirable consequences. In terms of inland port, availability refers to the readiness of the adequate resources to perform the daily operation. Inland port availabilities can be measured through port resilience, the readiness of different kinds of equipment and labour support, dredging maintenance, and congestion rate.

(i) *Port Equipment*. In order to perform daily operations such as handling cargo and stevedore operations, port authorities use different kinds of capital equipment, such as gang-tree/rubber-tree cranes, mooring instruments, forklifts, reach stackers, and towing vehicles. For the inland waterway port, gang-tree cranes and straddle carriers are most commonly used.

(ii) *Port Resilience*. Ability of a port to bounce back to its normal operating condition after any type of disruption such as adverse weather conditions, human-made error, and/or cyberattack. Resilience capacities are the strategies to recover a region/entity from any shock or external perturbation due to disruption. Resilience capacities can expressed by means of *absorptive capacity, adaptive capacity, and restorative capacity* of the corresponding system [35, 39, 51–53]. It is generally designed based on metastructure under internal deterioration and external perturbation [54].

Absorptive capacity is an endogenous feature of the system and is also considered to be the first course of defense to minimize the impacts of the disruption [25, 26, 39, 52]. Maintenance, availability of additional capital equipment, and skillful response team are the mainstay of the port absorptive capacity. *Adaptive capacity*, which is considered to be the midline of defense, is described as the ability of a system to self-organize itself and provide immediate solutions to cope with the external shock without any recovery activity [25, 26, 35]. Alternate routing and relocating of resources are the key factors germane to the adaptive capacity within port infrastructure. *Restorative capacity* considered to be the last line of defense is the degree to which a system can efficiently repair or restore from the degraded state [35]. Within the restorative capacity of port infrastructure, two salient determinants are identified: restoration of resources and restoration of service.

(iii) *Workforce*. Workforce is an asset to any port infrastructure. Operators and stevedores also ensure proper utilization of the available resources and reduce the delay during port operations such as loading and

Table 3: Modelling of variables contributed to port facility.

Variable Name	Modelling Technique	Modelling Description
Throughput	TNORM	Based on inland port statistics, a truncated normal distribution is used to approximate the annual throughput of an inland port with an average of 20 million ton/year.
Product Diversity	Trinagular	Product diversity is approximated with a triangular distribution with minimum, most likely, and maximum of 2, 3, and 5 respectively.
Types of Terminal	Arithmetic	Types of the terminal are fixed and equal to 3 to avail the proper terminal facility.
Warehouse Area	TNORM	Warehouse area is defined by truncated normal distribution with a mean of 7,5000 m^2.
Outdoor Ground Storage	TNORM	The outdoor storage area is approximated using truncated normal distribution with an average of 40 acres.
Dock-wall	TNORM	A truncated normal distribution is used to approximate the dock wall parameter of an inland port with an average of 700 m.
Terminal Facility	Comparative Expression	Threshold for throughput and product diversity are set as 20 million/year and 2 respectively while port should have exactly 3 types of terminal to avail the proper terminal facility.
Key Facilities	Comparative Expression	The key facilities will be suitable (true) for port operational activities if the parameters of dock-wall, warehouse area and outdoor ground Storage are higher than 600 m, 50,000 m^2, and 30 acres respectively.

Table 4: Modelling of equipment variable.

Variable Name	Modelling Technique	Modelling Description
Equipment	Comparative Expression	An IF logic is used for modelling an "equipment" node. The threshold for number of cranes and straddle is considered to be one In order to perform the regular operation, the port equipment requirements will be met (true state) if the number of cranes and straddle is more than one and otherwise not (false state).

unloading, recouping, grading, fuel transfer from vessel to the pier, gate operations, and others.

(iv) *Port Congestion. A* main parameter to measure port availability. Congestion occurs when vessels enter into a queue and wait for an extended period of time to access port facilities.

(v) *Dredging Maintenance*. Dredging is important for inland ports to maintain the desired water depth at their approach channels, specifically for those ports where the waterway accumulates silt quickly. Enhanced dredging capability also positively impacts the availability of the port.

3.1.5. Modelling of Port Availability. Boolean variables were used to model the contributors of port availability. For instance, the prior distribution of the resilience variable with two states of True = 93.35% and False = 6.65%, which means that there is an 93.35% chance that a strong resilient port infrastructure would contribute to increase the availability of the port facility, while there is a 6.65% chance that it may fail. In other words, the resilience of the port system is successful 93.35% (True state) and fails 6.65% (False state) of the time. The same logic is applicable for other Boolean nodes under port availability variables. Table 4 provides detailed model description of the equipment variables.

Port resilience and availability criterion is designed using NoisyOR function and equation is presented below:

$$\begin{aligned} &\mathit{Port\ resilience} = \mathit{NoisyOR}\ (\mathit{absorptiev\ capacity}, \\ &\quad 0.70, \mathit{adaptive\ capacity}, 0.70, \mathit{restorative\ caapcity}, \\ &\quad 0.80, 0.15) \end{aligned} \tag{8}$$

$$\begin{aligned} &\mathit{Port\ Availabilily} \\ &\quad = \mathit{NoisyOR}\ (\mathit{Dredging\ maintenance}, 0.50, \\ &\quad \mathit{labor\ support}, 0.50, \mathit{port\ congestion}, 0.20, \\ &\quad \mathit{port\ reslience}, 0.50, \mathit{equipment}, 0.50, 0.15) \end{aligned} \tag{9}$$

3.1.6. Port Economics (Criterion #3). Port economics: the solvency of the major stakeholders, the overall status of the global economy, and port pricing also influence the port economics.

Port associated cost consists of terminal-handling costs, port calling cost, and concession pricing.

(i) *Terminal-handling cost (THC)*: it is related to the cost for loading or unloading, container service and clearance, storage, repacking, and forwarding. It includes all services essential for moving the freight

Table 5: Modelling of variables contributed to port pricing.

Variable Name	Modelling Technique	Description
Terminal Handling Cost (THC)	TNORM	Based on inland waterway port data, the average terminal cost is the $6,500/barge with a variance of $25 and cost varies from The $5,000 to $8,000 based on the size of the barge and other related factors.
Port Calling Cost (PCC)	TNORM	Port calling cost varies from $1,800 to $3,800 depending upon the size of the vessel with an average of $2,500 dollar/ vessel.
Concession pricing (Upfront fee)	TNORM	Concession granting depends upon the area of the facility and follows a truncated normal distribution with an average of $60 million upfront fee.

Table 6: Modelling of port pricing variable.

Variable Name	Modelling Technique	Description
Port pricing cost	Comparative Expression	IF the THC, PCC and concussion grant are lower than $7000, $2,800 and $65 million, respectively then the port economy cost is within limit (true state), otherwise not (false state).

onwards through the port before being loaded onto a vessel. More precisely, beyond the sea freight, THC is the charge that is paid by shippers for handling the containers at the inland port.

(ii) *Port calling cost*: it is the costs related to all types of services offered to handle a ship or vessel. More precisely, it is the summation of prices to be paid for various services including access to the terminal, pilotage, time costs, damage and delay, and bunkering.

(iii) *Concession cost*: it is decided by the port governing body and it is the cost of acquiring a dedicated maritime facility such as a terminal, yard, or outdoor storage. It is mainly a leasehold agreement and used for a variety of reasons.

Tables 6 and 5 describe the modelling details of port pricing variables and its contributed factors, respectively.

NoisyOR function, which is discussed in the previous section, is applied to design the economic criterion as presented below.

$$\begin{aligned} &\mathit{Port\ Ecomonics} = \mathit{NoisyOR}\ (\mathit{Port\ pricing}, 0.50, \\ &\quad \mathit{solvency\ of\ major\ user}, 0.50, \mathit{economic\ climate}, \\ &\quad 0.50, 0.15) \end{aligned} \tag{10}$$

3.1.7. Port Service (Criterion #4). An inland port's service level indicator is highly integrated with response rate, service availability, container dwell time, and vessel transit time at the port.

(i) *Response rate*: a measure of port service including faster documentation, availability and quick updates of electronic information, early detection, and response to problems. The higher response rate reduces unnecessary cost pertaining to any port.

(ii) *Service availability*: it is a measure of port performance that refers to port services at any time of the day or the service is restricted for a fixed time. High service availability means the operational hours of a port is higher than normal and vice versa. Generally, for an inland waterway port the service hours vary from 8 to 24 hours per day.

(iii) *Dwell time*: dwell time is measured by the amount of time a container waits to be picked up at a marine terminal after being offloaded from a ship or vessel [55]. This is considered as a key benchmark for port's service level indicator. Port authority always experiences a constant challenge to keep the dwell time down while accommodating inbound and outbound vessels.

(iv) *Transit time*: transit time management is one of the main concerns of port authority. It is the amount of time that a vessel spends in different ports on the way to its destination port. This also includes waiting time dockside before loading/unloading.

3.1.8. Modelling of Port Service. As apparent from Figure 3, port service consists of four main contributors including response rate, service availability, dwell time, and transit time. Truncated normal distribution similar to what is explained in the previous section is applied to model the aforementioned four contributors. The modelling procedure of port service and its contributors are summarized in Tables 7 and 8. The modeling procedure of geographical location and port accessibility is summerized in Table 9.

3.1.9. Port Connectivity (Criterion #5). Connectivity refers to the level of ease that an inland port supports freight transportation through the supply chain network.

(i) *Geographical Location.* Some geographic areas possess natural advantages for business flourishment. It is beneficial for an inland waterway port to have a logistic cluster, a major supplier, and an intermodal connection within its vicinity. Geographical locations

Table 7: NPTs of the variables describing response rate, service availability, dwell time, and transit time.

Variable Name	Modelling Technique	Modelling Description
Response rate	TNORM	Based on the inland port statistics, the response rate of inland port varies from 85% to 95% with an average of 90%.
Service availability	TNORM	At the worst possible scenario, the port operating hours are not lower than 16 hours and at the best possible the port provides 24 hours service a day.
Dwell time	TNORM	Dwell time is modelled with a truncated normal distribution with mean, LB, and UB of 3, 1, and 4 hours respectively.
Transit time	TNORM	A truncated normal distribution is used to approximate the transit time of a vessel with an average of 24 hr.

Table 8: Modelling of service variable.

Variable Name	Modelling Technique	Modelling Description
Port Service	Comparative Expression	If the values of response rate or service availability are greater than 90% or 12 hours, respectively AND dwell time or transit time is lower than 3 or 30 hours, respectively then the satisfactory service level is achieved (true state), otherwise not (false state)

Table 9: NPTs of the variables describing the contributor to geographical location and port accessibility.

Variable Name	Modelling Technique	Modelling Description
Distance to Logistic & Industrial Area	Arithmetic	Distance to logistic & industrial cluster is constant: 75 miles.
Distance to Major Supplier	Arithmetic	The distance between port and major supplier is constant: 50 miles.
Distance to Intermodal Connection	Triangular	The distance between the port and the intermodal connection is modelled with triangular distribution with mean, LB, and UB of 50, 35 and 65 miles respectively.
Geographical Location	Comparative Expression	Based on the historical data, if the logistics cluster, major supplier, and intermodal connection are within 75, 50, and 50 miles from the inland port location, then port has suitable geographical location for trade and commence (true state), otherwise not (false).
Port accessibilities	Boolean	We assume that 90% of the time, the port is accessible by all required modes of transportation. On very few occasions, port entire accessibility is halted by natural calamities, human error and/or cyber-attack.

associated with modal accessibility and availability of inland regional access influence shaping of the development of surrounding locality [56]. All these criteria boost productivity, save time, lower the logistic cost, and provide access to global markets.

(a) *Proximity to the industrial area and logistics cluster*: logistics clusters provide integrated services in logistics. If the port location is close to the logistics cluster center, the port may perform better than port locations farther away from the cluster center. Port proximity to industrial areas has a great impact on port choice.

(b) *Proximity to major supplier*: proximity to major suppliers will enhance national and international trade throughout the port. Traders can exploit economies of scale in shipping products and, in turn, will be benefitted from in time delivery and lower inventory holding costs.

(c) *Proximity to intermodal connection:* the strength of inland intermodal transportation network includes the availability of railway, roadway, and rail spur in the port province. The ports that are close to intermodal connection generally get better transportation facilities, such as highways, railroads, and airports.

(ii) *Port Accessibility*. Port accessibility means the port location can be approachable by different modes of transportation. Port accessibility depends upon the location and the overall infrastructure of the port.

3.1.10. Modelling of Port Connectivity. NoisyOR function, as discussed in the previous section, is used here to calculate the conditional probability of connectivity criterion as defined in

$$\begin{aligned} & \textit{Port Connectivity} = \textit{NoisyOR}\,(\textit{port accessibility}, \\ & \quad 0.75, \textit{geographical location}, 0.75, 0.20) \end{aligned} \tag{11}$$

The above equation means that port accessibility and geographical locations are equally responsible to obtain desired connectivity and there are other hidden factors directly or indirectly influencing to achieve preferred port connectivity.

3.1.11. Port Environment (Criterion #6). Two main subcriteria, emission at port and probability of natural disaster,

Table 10: Modelling of variables related to emission at the port.

Variable Name	Modelling Technique	Description
CO_2 Level	TNORM	The level of CO_2 emission (million tonnes/year) follows a truncated normal distribution (TNORM) with an average of 15 and variance of 2.5. The level of CO_2 emission (million tonnes/year) never goes below 12 (lower bound) and 18.5 (upper bound), according to the historical data for the inland waterway port.
NO_x Level	TNORM	The level of NO_x (million tons/year) follows a truncated normal distribution with an average of 0.2, the variance of 0.005 with lower bound and upper bound of .1 million tons/year and 0.4 million tons/year, respectively.

Table 11: Modelling of emission at port variable.

Variable Name	Modelling Technique	Modelling Description
Emission at Port	Comparative Expression	An IF logic is used for modelling "emission at port" node. The threshold for CO_2 and NO_x level are considered to be 18 and 0.2 respectively. The emission index will meet (true) if the levels of CO_2 and NO_x at the port are less than 18 million tons/year and 0.2 million tons/year respectively.

Table 12: NPT for port environment.

Emission	True		True	
Disruption	False	True	False	True
False	0.2	0.15	0.15	0.05
True	0.8	0.85	0.85	0.95

are found as the main determinants to the environmental criterion for port performance.

(i) *Emission at port*: shipping emission has a substantial impact on the overall environment of the port. Most shipping emissions in ports account for discharges of CO, SO_x, and NO_x. The quantity of total emissions depends on the type and size of vessel berth at the port. At the same time, emission due to regular port equipment also accounts for deterioration of the air quality of the port. In order to reduce these emissions, strong policy along with public awareness is required.

(ii) *Probability of natural disaster*: the inland waterway port is often susceptible to different natural disasters such as hurricanes, cyclones, drought, or flood, combined with the prevailing port temperature and humidity.

3.1.12. Modelling of Port Environment. Figure 3 shows that port environment mainly conditioned upon two determinants: disruption of probability and emission at the port. The Boolean node is used to express the probability of disruption and emission at the port. For instance, disruption probability of 15% means that, according to the historical data, there is a 15% chance that the inland port might be impacted by adverse weather conditions. Tables 10 and 11 show the procedures of modelling for emission at the port and its contributed variables.

The NPT is the probability table that summarizes the occurrence probability between the causal relationship nodes. NPT can be developed manually or achieved by eliciting the distribution or related expression. For a node without its parent node, the NPT would be simply the probability distribution of that specific node. NPT for port environment is shown in Table 12.

3.1.13. Modelling of Port Performance Indicator. The ultimate target node "port performance index" is conditioned on its contributed criteria *(i) port facility, (ii) port availability, (iii) port economics, (iv) port service, (v) port connectivity, and (vi) port environment.* The posterior probability of PPI is calculated as the weighted sum of its contributed criteria. Initially, it is assumed that the weight of each factor is equally distributed. The general equation associated with a weighted mean (WMEAN) is presented in (12), where *(i)* is the number of variables connected (six in this case) to the weighted average node of port performance index (see Figure 2) and W_i is the weight associated with the ith variable.

$$\text{WMEAN} = \sum W_i A_i, = 1, 2 \ldots n, \quad \forall \text{i} = 1 \;\; 0 < W_i < 1, \;\; \sum_i W_i = 1 \tag{12}$$

To compare the port performance index, based on above-mentioned criteria, the probability the probability of PPI being true is 87.82%, meaning that there is 87.82% likelihood (chance) that the specific port will meet the performance standard based on the cited criteria.

4. Validation of the Model

In order to validate the structure of the BN model, apart from traditional methods, *sensitivity analysis* (SA) is considered a powerful technique. It is a useful approach to examine the impact of the contributors on the target node within the same model, i.e., which node has more impact to its connected node. This is obtained by recalculating the outcomes of the targeted node under possible alternative assumptions. The object of the SA is to check that the outcomes generated from the propagation analysis are consistent with the expert's expectation. To obtain more insights and better understanding of the simulation model, we used *AgenaRisk* software

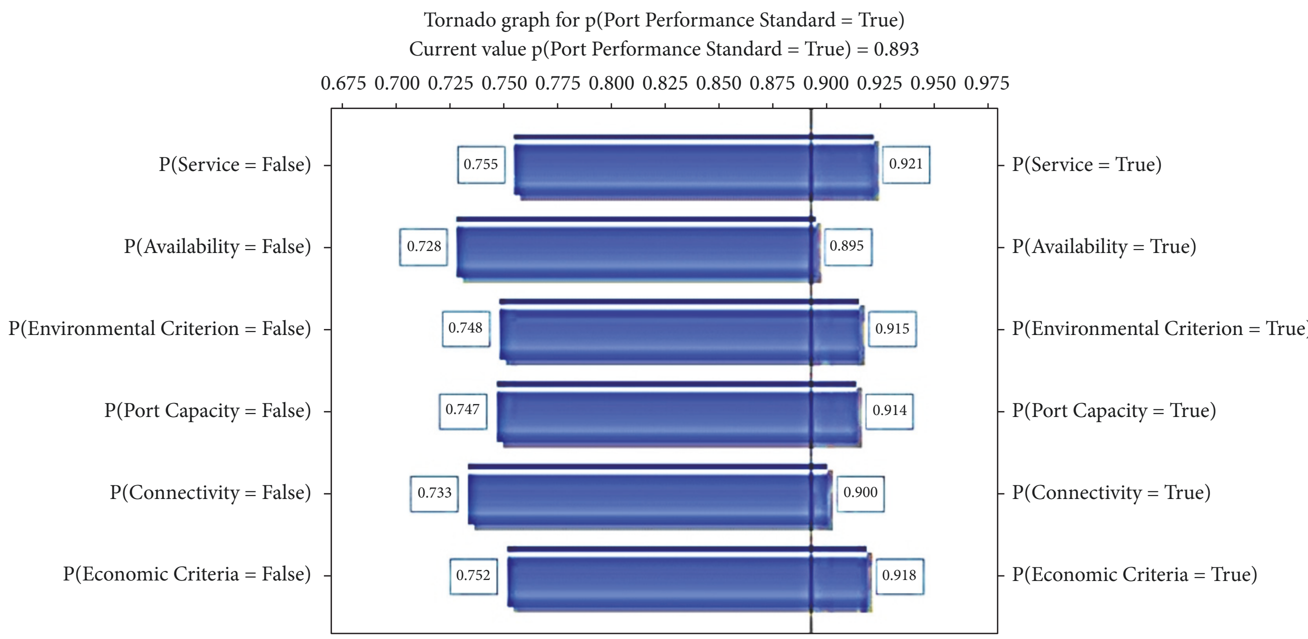

Figure 4: Sensitivity analysis of PPI.

to investigate the extent to which the six key performance contributors affect the port performance index. We performed SA on PPI as a target node with respect to its causal factors including *(i) port facility, (ii) port availability, (iii) port economics, (iv) port service, (v) port connectivity, and (vi) port environment* as subsequently shown in Figure 3. Tornado charts, generated during the SA analysis, identified the lowest and highest values of a posterior probability for each possible state of the target node if specific observations are inputted into the model. To be more specific, the length of the bars corresponding to each sensitive node in the tornado graph illustrates a measure of the impact of that corresponding node on PPI. Figure 4 shows the impact of those variables when the PPI is "true." It is apparent from Figure 4 that the length of the bar chart for all the selected variables is almost same; however, port service has a slightly higher impact on PPI than other variables, whereas port economics has a lower impact on PPI among all the variables. To elaborate, from Figure 4 it is also apparent that the probability of PPI ("true") for the first port given the result of port service goes from 0.755 (when port service is "false") to 0.921 (when port service is "true"). In other words, the probability of PPI for first port is 0.921 when the port service is met. This range (0.755–0.921) is exactly the bar that is plotted in the tornado graph illustrated in Figure 4. This range varies from 0.752 to 0.918 for the port economics which implies port economics has the lowest impact on the PPI among all the variables. From Figure 4 it can also be interpreted that the probability of PPI for the port is more sensitive to the changes in the states of port service and least sensitive to changes in port economics. It can be concluded that although all the factors have almost same importance to the variability of PPI, port service ranked top in terms of contribution to the variability of PPI, and therefore the port authorities and top management should emphasize more on port service than others determinants.

5. Propagation Analysis

The feature of the BN to disseminate the effect of evidence through the network is defined as "propagation analysis". Special types of reasoning can be done through propagation analysis. During propagation analysis, different evidences (observations) can be entered anywhere in the underlying BN model to update the marginal probabilities of all unobserved variables. In this section, we have conducted forward propagation analysis to predict the probability distribution of PPI under the combination of the aforementioned six contributors. The related probability is represented in (13) (Zhou, 2018).

$$P\left(T = State_t\right) = \sum_{n=1}^{n} (P\left(PPI = State_t \mid A_1 = a_j, A_2 = a_j, \ldots A_n = a_j\right) xP\left(A_1 = a_j, A_2 = a_j, \ldots A_n = a_j\right) \quad (13)$$

where n refers the number of parent nodes and a_j is the ith state of the parent node. $(P(PPI = State_t \mid A_1 = a_j, A_2 = a_j, \ldots A_n = a_j)$ is conditioned probability distribution when T= State$_t$.

During the *forward propagation* analysis, we have designed two scenarios *(1)* pessimistic and *(2)* optimistic. Scenario 1 (pessimistic scenario) accounts for two assumptions: *(i)* the service hours of the port is set to 8 hours instead of truncated normal distribution with a mean of 16 hours and

Table 13: Summary of propagation analyses.

Scenario	Description of the Scenario	PPI	Standard of the Port	Significance of the propagation	Remarks
Base Case	Underlying BN Model	87.82%	Class B	-	-
Scenario 1 (Pessimistic Scenario)	Service hr = 8hr, Transit time=36hr (Other variables remain unchanged)	74.87%	Class C	Shows how probability of PPI changes with service level (service availability and transit time)	*Port Service* criterion has a significant impact on the probability of PPI.
Scenario 2 (Optimistic Scenario)	Throughput=30 million ton, Dredging Maintenance=100% True, Port environment =100 True% (all environmental criteria are met)	91.28%	Class A	Shows how probability of PPI varies with port facility (throughput), port availability (dredging maintenance) and port environment.	*Port facility, port availability* and *port environment* have less impact on the probability of PPI compared to port service

(ii) the transit hours of the port are set to 36 hours in lieu of truncated normal distribution with an average of 30 hours. Scenario 1 measures the changes in the probability of PPI of the first port if the service hours reduced to a constant value of 8 hours and transit time increased to a constant value of 36 hours. From Figure 5, the probability of PPI of the first port significantly reduced from 87.82% to 74.87% which indicates the importance of service hours and transit time on PPI. Scenario 2 (optimistic scenario) simulates the impact of throughput, dredging maintenance, and port environment on PPI for the inland port. We set the throughput to 30 million/year, dredging maintenance and environmental as 100% instead of their prior distribution parameters which increases the PPI from 87.82% to 91.28% (see Figure 6). This type of propagation analysis gives the capability to decision makers to make any number of observations especially on variables with inherent uncertainty and measures.

A summary of propagation analyses is s given in Table 13. Scenario 1 and 2 are illustrated in Figures 5 and 6, respectively.

6. Conclusion

In this study, a novel dimensionless metric named port performance indicator (PPI) is introduced to assess the level of port performance based on six basic determinates named: *port facility, port availability, port economics, port service, port connectivity, and port environment.* In order to calculate the probability of PPI, we developed a Bayesian framework that captures the possible factors and subfactors pertaining to the level of port performance. The PPI indicates the level of performance that will be met by a specific port. It also provides a better understanding regarding the performance of a specific port under uncertainty. The PPI will aid port stakeholders in making better decisions in terms of the management of port supply chain and infrastructure. Such decisions include the number of port service hours, scaling port throughput, and others. In real-world practices, it is quite difficult to predict a port performance because of uncertainty and ambiguity (e.g., operational uncertainty, disruption uncertainty, etc.). In response, predicting the PPI through the Bayesian approach can help to substantially reduce this uncertainty and will ensure better visibility for decision-making. Belief propagation feature of the Bayesian approach allows practitioners to run different future scenarios where assumptions and alterations in conditions or states can be tested and verified. Belief propagation analysis also demonstrates the weightage of interdependency among the different variables of the underlying BN structure. The BN structure is also validated through sensitivity analysis. The general interpretation of the sensitivity analysis indicates that all six criteria are important to predict PPI; however, port service has a slightly higher impact and port economics has a lower impact among all factors in predicting the probability of PPI. The novelty of this work is summarized.

(i) The development of a model to assess port performance indicator (PPI).

(ii) The underlying determinates pertaining to port performance were identified and classified with respect to six main factors named: *port facility, port availability, port service, port economics, port connectivity, and port environment.*

(iii) The proposed model is then tested and validated through different types of analysis to draw better managerial insights to handle uncertainties. Results indicate that all the factors have almost same importance to the variability of PPI, port service ranked top in terms of contribution to the variability of PPI, and therefore the port management should stress more on service criterion than others factors.

(iv) Demonstrate the efficacy of BN as an effective tool in solving transportation and logistics management problems.

This study can be extended in several research directions. In our study, NPT has been defined based on subjective judgment (expert opinion) and frequentist approach (historical data). Other methods such as swing weights, Delphi technique, and the classical method can be used to improve the accuracy of NPT. Furthermore, a deep investigation is required to identify the other related factors that might indirectly impact the PPI.

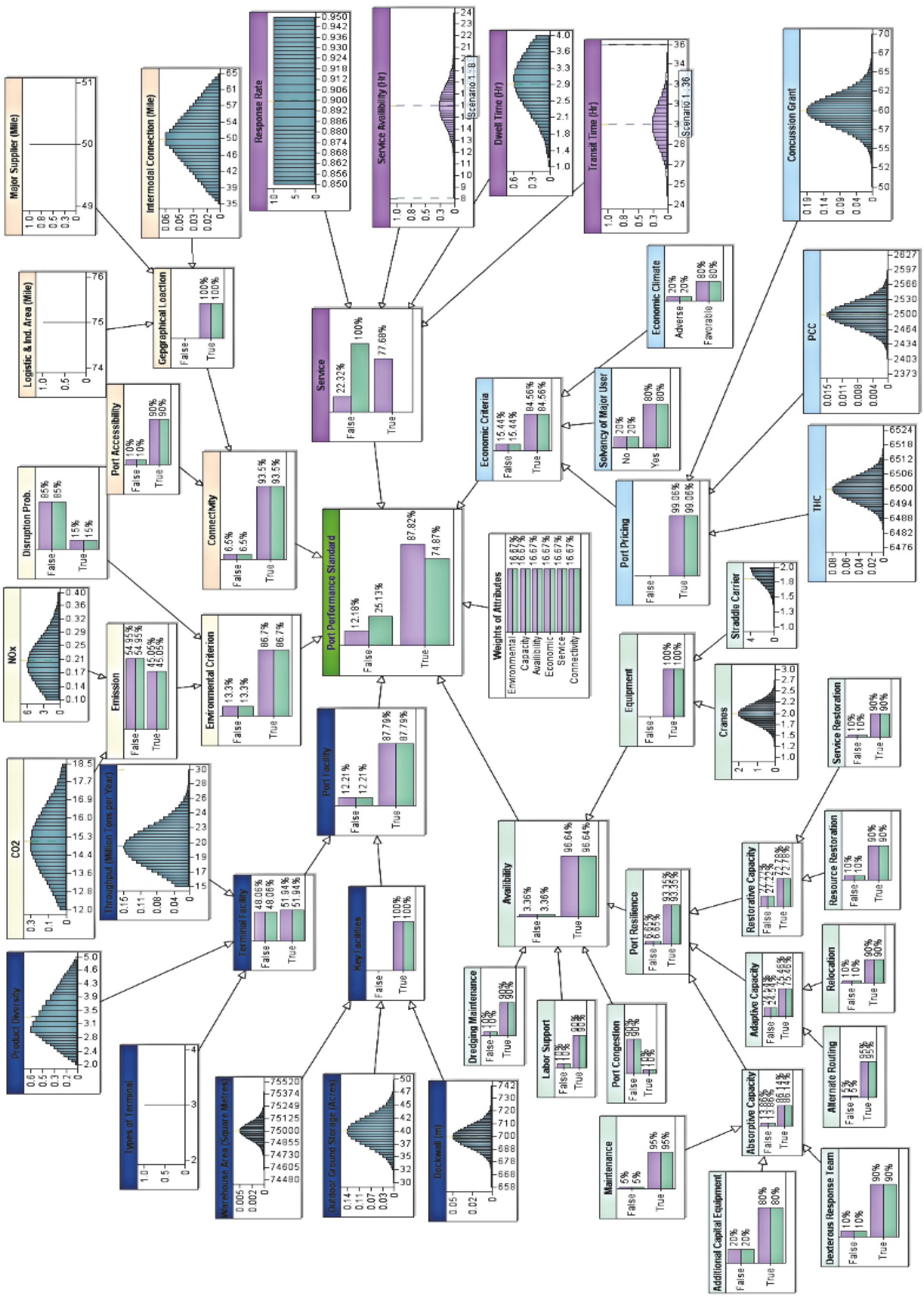

FIGURE 5: The developed BN model for scenario 1.

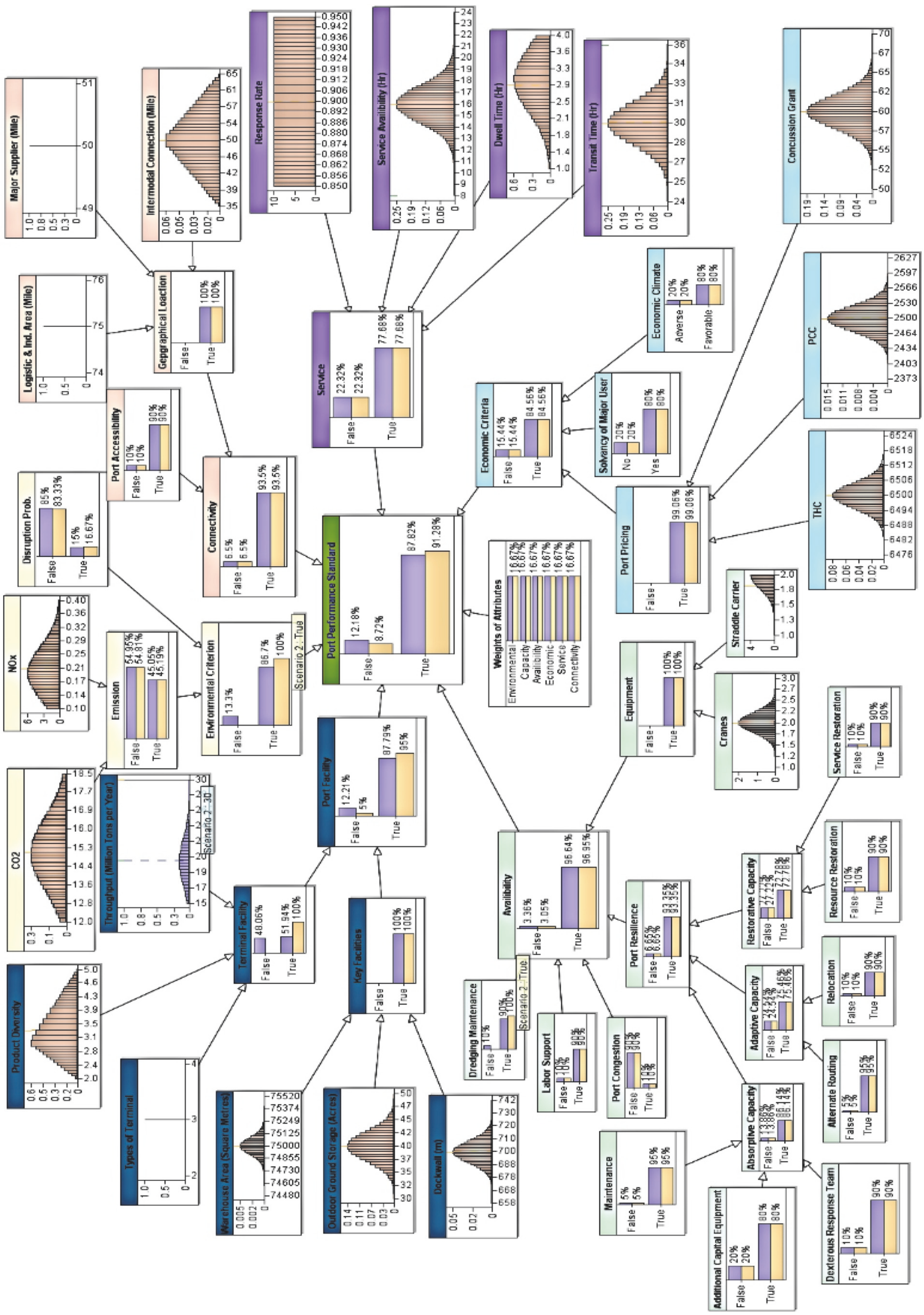

Figure 6: The developed BN model for scenario 2.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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