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Original article

Selecting Tanker Steaming Speeds under Uncertainty: A Rule-Based Bayesian Reasoning Approach

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Abstract

In the tanker industry, there are a lot of uncertain conditions that tanker companies have to deal with. For example, the global financial crisis and economic recession, the increase of bunker fuel prices and global climate change. Such conditions have forced tanker companies to change tankers speed from full speed to slow speed, extra slow speed and super slow speed. Due to such conditions, the objective of this paper is to present a methodology for determining vessel speeds of tankers that minimize the cost of the vessels under such conditions. The four levels of vessel speed in the tanker industry will be investigated and will incorporate a number of uncertain conditions. This will be done by developing a scientific model using a rule-based Bayesian reasoning method. The proposed model has produced 96 rules that can be used as guidance in the decision making process. Such results help tanker companies to determine the appropriate vessel speed to be used in a dynamic operational environmental.

Keywords: Tanker, Vessel Speed, Uncertainty Treatment, Rule-based Method, Bayesian Reasoning Method, Decision Making Technique

I. Introduction

The uncertainties of the international marks in 2008/2009 such as, the financial crisis and economic recession, the increase of bunker fuel prices and global climate change have stimulated tanker companies to change tankers speed from full to super slow steaming speeds. A previous study has discussed the necessity of steaming speed under uncertain conditions on the Aframax/VLCC tanker sector (Nikolic, A.Klanac, & P.Kumar, 2011), on the container sector (Abdul Rahman, 2012), and its economic and environmental impacts on the shipping industry (Yin, Fan, Yang, & Li, 2014).

However, this scope of study is focused solely on the tanker industry and the four levels of vessel speed namely 1) full speed (FS), 2) slow speed (SS), 3) extra slow speed (ESS) and 4) super slow speed (SSS) (Bonney and Leach, 2010). Therefore, the objective of this paper is to present a methodology for determining the vessel speeds of tankers that minimize their running cost of the vessels for under uncertain conditions. A scientific decision for making models will be developed in this study using a Rule-based Bayesian Reasoning (RBR) method.

II. Literature Review

Most tanker players have enjoyed having a high profit margin since the year 2000. However, the global economy recession in late 2008, had a huge impact that affected not only the containership industry but the tanker industry as well. The world gross domestic product (GDP) fell by 1.9% (Kontovas and Psaraftis, 2011). Due to this, the tanker market demand decreased by 0.6% from the middle of 2008 to the middle of 2010. On the tanker supply side, the tanker supply increased by 19% for the same period (INTERTANKO, 2011). Obviously, tanker demand and supply have been in a state of flux (imbalanced) during the particular period. As reported by INTERTANKO (2014), in 2009, 43.9 million dwt tankers have been delivered, which was +12.7 million dwt more compared to the 31.2 million dwt in 2008. Later on, the number of tanker deliveries have decreased year on year from 37.3 million dwt in 2010, to 36.9 million dwt in 2011, to 34.2 million dwt in 2012 and 24.3 million dwt in 2013.

According to Devanney (2011), the bunker price is a key factor that controls the shape of the supply curve. If the market is weak and the bunker price is high, the vessel will slow down. If the market is strong and bunker prices are low, the vessels will speed up. According to Abdul Rahman (2012), the history of the bunker prices shows the increase of bunker prices from $180.32 per tonnage in 2004, to $261.90 in 2005, $313.18 in 2006, $372.82 in 2007, spiking at $505.62 in 2008 and suddenly falling to $371.87 in 2009. However, bunker prices have steadily increased to a level of above $615.93 in 2013. This uncertain situation will automatically affect the performance of tanker companies, voyage costs and freight rates. The freight rates depend on many factors including the cost of operating the vessel, the capital costs of buying the vessel and the cost of the shore-side operation, which covers office personnel, rent and marketing (Stopford, 2009). According to Lun et al. (2013), the history of freight rates shows the decrease of freight rates from $196.99 per million tonnes in 2004, to $159.52 in 2005, $151.68 in 2006, $118.75 in 2007, spiking at $180.34 in 2008 and then suddenly falling to $65.53 in 2009. However, the freight rates have steadily increased to a level of above $98.78 since 2010.

Having said that, more tanker vessels have been laid up due to the sharp increase of bunker fuel price, low freight rates, the delivery of many new tankers and the sharp increase of operation cost (Ranheim, 2010). By laying up such vessels, shipping companies have not gained any income. Again, the uncertainty caused by freight rates has fuelled shipping companies to analyse the importance of making the right call when deciding what speed the vessel should operate at.

III. Background of Methods

3.1. A Rule-Based Method

A rule-based method consists of *if-then* rules. These *if-then* rule statements are used to formulate the conditional statements that comprise the complete knowledge base. A single *if-then* rule assumes the form 'if *x* is A then *y* is B' and the *if* part of the rule '*x* is A' is called the *antecedent* or *premise*, while the *then* part of the rule '*y* is B' is called the *consequent* or *conclusion* (Abraham, 2005; Yang et al. 2009). A belief rule-base consists of a collection of belief rules and is defined as follows (Liu et al. 2005; Yang et al. 2006):

$$R_k: IF A_1^k and A_2^k and \dots and A_M^k,$$
$$THEN\{(\beta_{1k}, D_1), (\beta_{2k}, D_2), \dots, (\beta_{Nk}, D_N)\}, (\sum_{i=1}^{N} \beta_{ik} \le 1) \quad (1)$$

where β_{ik} ($i \in \{1, \dots, N\}$; $k \in \{1, \dots, L\}$, with L being the total number of the rules in the rule base) is the belief degree to which D_i is believed to be the consequent if, in the *k*th packet rule, the input satisfies the packet antecedents $A^k = \{A_1^k, A_2^k, \dots, A_M^k\}$. If $\sum_{i=1}^{N} \beta_{ik} = 1$, the *k*th packet rule is said to be complete; otherwise, it is incomplete. Note that ($\sum_{i=1}^{N} \beta_{ik} = 0$) denotes total ignorance about the output given the input in the *k*th packet rule.

3.2. A Bayesian Reasoning Method

A Bayesian Networks (BN) method was developed by Bayes in 1761 and Bayes' Theorem was published in 1763 (Bernardo and Smith, 1994). The Bayesian reasoning method can be applied for combining rules and generating final conclusions. A BN method consists of nodes, arcs and an associated set of probability tables. Nodes represent random variables. Arcs are used to represent the direct probabilistic dependence relations among the variables. Each relationship is described by an arc connecting an influencing (parent) node to an influenced (child) node and has its terminating arrowhead pointing to the child node. A *Hugin* (Korb and Nicholson, 2003) software tool will be used in this paper for representing the model outcomes. Further detailed information can be found in literature by, Wang and Trbojevic (2007), Heckerman *et al.* (1995), and Eleye-Datuba et al. (2006). In general, Bayes's theorem is a mathematical algorithm used for calculating posterior probabilities. The Bayesian reasoning method can be applied to combining rules and generating final conclusions such as the prior probability of D_i ($i \in \{1, 2, \ldots, N\}$) which can be computed as follows (Yang et al., 2008):

$$P(D_i) = P\left(D_i \,\middle|\, A_1^k, A_2^k, \ldots, A_M^k\right) P\left(A_1^k\right) P\left(A_2^k\right) \ldots P\left(A_M^k\right) \quad (2)$$

where A_i^k ($i \in \{1, 2, \ldots, M\}$; $k \in \{1, \ldots, L\}$) is the referential value of the ith antecedent attribute in the kth rule. M is the number of antecedent attributes used in the kth rule and L is the total number of rules in the rule base. $P(.)$ denotes the probability.

IV. An Assessment of a Tanker Steaming Speed under Uncertainty

Step 1. Model Development

Uncertain conditions such as the financial crisis, economic recession and the increase of bunker fuel prices has had a high impact on the shipping industry. Therefore, in order to minimize the cost of the vessels, a model has been developed using a Bayesian network method (Section 3.2) incorporating a *Hugin* software tool. In addition, a bottom-up approach has been introduced in designing the model. The bottom-up approach can be defined as an approach that begins with details and works up to the highest conceptual level (Abdul Rahman et al. 2012). For example, the node "Economy (Ec)" is influencing the nodes "Global Factor (GF)" and "Ship Value (SV)" (figure 1). In this study, there are seven root nodes (parameters) that have been identified from the literature described in Section 2 namely 1) "Operational Cost (OC)", 2) "Voyage Cost (VC)", 3) "Bunker Prices (BP)", 4) "Emissions (Em)", 5) "Economy (Ec)", 6) "Ship Demand (SD)" and 7) "Ship Supply (SS)". The definition of root node is the node which has no parent. Furthermore, all the nodes except the goal node "Vessel Speed (VS)" have been grouped into three groups of nodes, namely 1) "Cost Factor (CF)", 2) "Global Factor (GF)" and 3) "Vessel Factor (VF)". The purpose of grouping all the nodes except the node "VS" is to simplify the calculation process without missing the input values and the goal of the model. Each node in the proposed model has a minimum of two states and a maximum of four states. Each state has its specific meaning. For example, the same meaning of the states "high" and "low" for the node "BP" have been referred to the paper written by Abdul Rahman et al. (2012). Finally, the proposed model has been developed, incorporating 14 nodes with the purpose of assisting shipping companies to make a decision in selecting the appropriate vessel speed. The proposed model can be applied in different situations concerning routes, tanker's sizes and vessel characteristics. The output may be different if these factors are adopted without affecting the backbone of the proposed model.

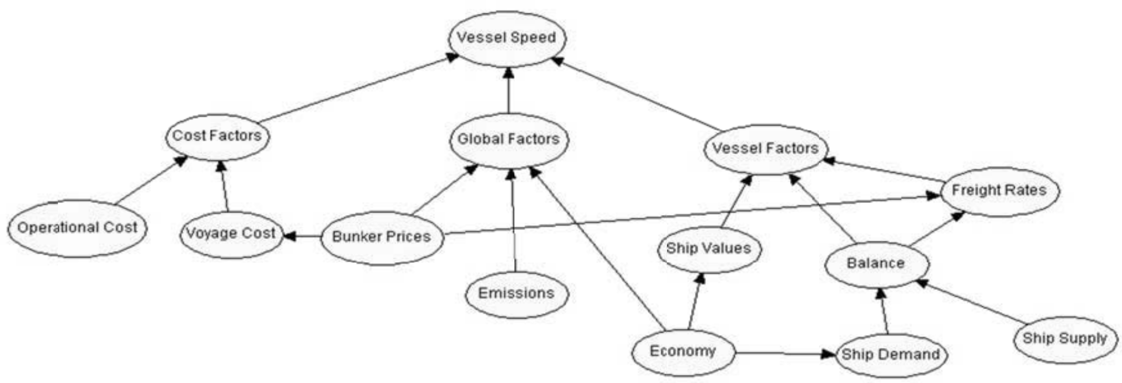

Figure 1: A proposed model for analysing the vessel speed

Step 2. Data Collection Process

In reality, shipping companies can use their dataset to obtain the actual outcomes based on the uncertain situations they face. However, both quantitative and qualitative dataset will be used in this study and they are obtained from different sources. Given the node "Bunker Prices" as an example for the quantitative dataset, this node has two states 1) "*high*" and 2) "*low*". To analyse this particular node, the bunker fuel price ($/tonne) has been collected from Clarkson Research Services. Such a set of data contains 13 values representing annual data from 1998 to 2010. Such data is presented as a line graph allowing the determination of the boundary between the two states, using a mean value algorithm. The mean value in this case can be calculated as follows:

$$Mean = \frac{\Sigma X}{\Sigma N} \quad (3)$$

Eq. 3 is used for determining the mean value of the node "BP". ΣX is the total bunker price of the 13 years. This amount can be computed by calculating the entire price per tonne from 1998 to 2010. As a result, the total bunker price is $3,254.47. ΣN is the total number of years. There are 13 years in total between from 1998 to 2010. Based on the information ΣX and ΣN, $250.34 is the mean value of the node "Bunker Price". Therefore, every single price of the bunker in the range between $0.00 and $250.34 is considered as the state "*low*" category, while the bunker price from $250.35 and above will be grouped as the state "*high*". Six of the 13 bunker prices values are grouped in the state "*high*" and the other seven are grouped in the state "*low*". As a consequence of this the probability value of the state "*high*" is (6/13) = 0.4615, while the probability value of the state "*low*" is (7/13) = 0.5385.

The same concept and calculation technique is applied to the node "BP" and is used for the following nodes, 1) emissions, 2) economy, 3) operational cost, 4) voyage cost, 5) ship demand and 6) ship supply. To obtain the qualitative dataset, a set of questionnaires were sent to three selected experts with a shipping background. In the set of questionnaires, a set of guidance related to the probability rate was attached. Table 1 illustrates the range of the probability levels that would give an idea to the experts, in order for them to provide their judgments according to the situation(s) given in the questionnaire. Basically, this probability rate is divided into 2 parts which are 1) more cost (right hand side) and 2) normal cost (left hand side). This guidance starts from zero as a middle value to differentiate the probability rate between the right and left hand sides. The probability rate used in table 1 has been adopted from a paper written by Abdul Rahman et al. (2012).

Table 1: The transformation process from the probability rate to the probability value

Left Hand Side			Right Hand Side	
Probability rate	**Probability value of the state "normal cost"**		**Probability rate**	**Probability value of the state "more cost"**
5	0.0		0	0.5
4	0.1		1	0.6
3	0.2		2	0.7
2	0.3		3	0.8
1	0.4		4	0.9
0	0.5		5	1.0

All the feedback received from the experts was transformed into a probability value ranging from 0 and 1. Zero rating is a middle value that can be translated as 0.5 of the probability value, while the probability rating from 1 to 5 on both the right and left hand sides can be transformed into the probability value as shown in table 1. The total probability value of each node must be add up to 1.0, for instance 0.43 (high) + 0.57 (low) = 1.0. Table 2 illustrates the basic foundations of the probability rate applied in this study.

Table 2: The fundamental concept of the probability rate and probability value

0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
→										
5 normal	4	3	2	1	0	1	2	3	4	5 More

Due to there being more than one expert, the average probability value for every single state of each node has to be calculated using the following equation:

$$\text{Average probability value} = \frac{\text{Total probability rate given by experts for the same state/event}}{\text{Total number of experts}} \quad (4)$$

As an example, the node "Cost Factors" will be used to demonstrate how this formula functions. Such a node has two states 1) "*more cost*" and 2) "*normal cost*". If the nodes are "*OC=more cost*" and "*VC=more cost*", the selected experts have to provide their judgment on the probability rate of the node "Cost factors". The experts A, B and C ticked number five on the right hand side of a probability rate (table 2). Thus, this probability rate can be transformed into a probability value as 1.0 for the state "*more cost*" and automatically the probability value of the state "*normal cost*" is (1.0 – 1.0) = 0.00. The average probability value can be computed using Eq. 4 for each state. For example, if the nodes are "*OC=more cost*" and "*VC=more cost*", the average probability value of the state "*more cost*" for the node "Cost Factors" is equal to 1.0 (3 ÷ 3 = 1), while the average probability value of the state "*normal cost*" is equal to 0.0 (0 ÷ 3 = 0). Such average values will be used as a set of qualitative input data and transferred into a *Hugin* software tool for calculating the final outcomes. This calculation technique is applied to all qualitative data (for instance, 1) global factor, 2) vessel factor, 3) ship values, 4) balance and 5) freight rates) in order to obtain the average probability values for each node.

Step 3. Establishment of a Rule-Based Method

Three fundamental attributes 1) VF, 2) GF and 3) CF are considered as the antecedent attributes in *IF-THEN* rules, while the node "VS" is expressed as the conclusion attribute. To construct the rule-base, a number of linguistic terms or variables have to be defined to express the three antecedent attributes and conclusion. To estimate, "VF_i*{i = 1(high), 2(average), 3(low)}*", "GF_j*{j = 1(good), 2(average), 3(fair), 4(poor)}*", "CF_k*{k = 1(more cost), 2(normal cost)}*" and "VS_l*{l = 1(full speed), 2(slow speed), 3(extra slow speed), 4(super slow speed)}*". By using these linguistic terms and expert judgments', the rule-base with a belief structure for the node "VS" is partially summarised in table 3. By using Eq. 1, the rule-based with a belief structure can be performed as follows:

R1: IF CF1=more cost and GF1=good and VF1=high,

THEN {(0.2000, full speed (VS1)), (0.8000, slow speed (VS2)), (0.0000, extra slow speed (VS3)), (0.0000, super slow speed (VS4)).

Table 3: The rule-based with a belief structure for the node "VS"

Rules	**Antecedent Attributes**			**Vessel Speed (VS)**			
No	**Cost Factors (CF)**	**Global Factors (GF)**	**Vessel Factors (VF)**	**FS**	**SS**	**ESS**	**SSS**
1	more cost	good	high	0.2	0.8	0.0	0.0
2	more cost	good	average	0.6	0.4	0.0	0.0
3	more cost	good	low	0.8	0.2	0.0	0.0
…	…	…	…	…	…	…	…
24	normal cost	poor	low	0.0	0.0	0.3	0.7

Step 4. Bayesian Reasoning Method

The child node "VS" has three parent nodes which are 1) VF, 2) GF and 3) CF. To demonstrate the calculation of the selected nodes using a BN theorem, the *CPT*s of the nodes "Bunker Prices" and "Voyage Cost" are given as follows:

CPT for Bunker Prices (BP) (without condition)

BP	
high	0.4615
low	0.5385

For example, *P*(*BP=high*) = 0.4615.

CPT for Voyage Cost (VC)

VC	*Bunker Price (BP)* *high*	*Bunker Price (BP)* *low*
more cost	1.0000	0.0000
normal cost	0.0000	1.0000

For example, conditional probability *P*(*VC=normal cost* | *BP=low*) = 1.0000.

By using the information in the *CPT* of the node "Voyage Cost", the prior probability value of

"*VC=more cost*" can be computed as follows:

P(*VC=more cost*) = *P*(*VC=high* | *BP=high*) × *P*(*BP=high*) + *P*(*VC=more cost* | *BP=low*) × *P*(*BP=low*)

= (1.0000 × 0.4615) + (0.0000 × 0.5385) = 0.4615

The prior probability value of "*VC=more cost*" is known to be 0.4615, while the prior probability value of "*VC=normal cost*" is 1.0000 – 0.4615 = 0.5385. These values can also be calculated using the *Hugin* software as shown in figure 2.

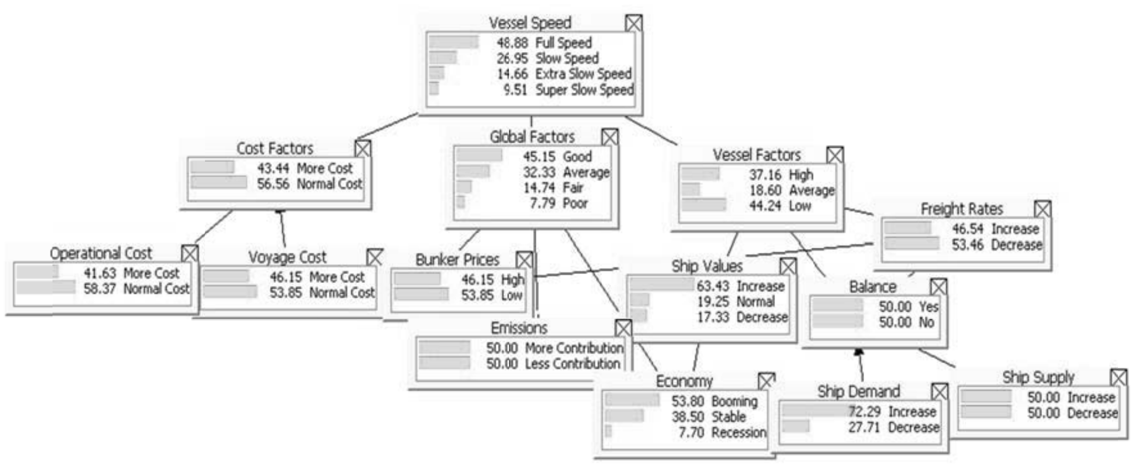

Figure 2: Prior probability values of all nodes in the BN model

After calculating the prior probability values of all parameter nodes, the posterior probability value of the goal node can be computed using Eq. 2. For example, given *"OC=normal cost"*, *"BP=low"*, *"Em=less contribution"*, *"Ec=booming"*, "*SD=increase*" and *"SS=increase"*, the posterior probability values of $P(VS \mid CF_k, GF_j, VF_i)$ are computed as follows:

$$P(VS) = \sum_{k=1}^{2}\sum_{j=1}^{4}\sum_{i=1}^{3} P(VS \mid CF_k, GF_j, VF_i)\, P(CF_k)P\big(GF_j\big)P(VF_i)$$

$$= P(VS|CF_2, GF_1, VF_3)P(CF_2)P(GF_1)P(VF_3)$$

(The other products of $P(CF)$, $P(GF)$ and $P(VF)$ are 0)

= $(1.0000, 0.0000, 0.0000, 0.0000) \times 1.0000 \times 1.0000 \times 1.0000$

= $(1.0000, 0.0000, 0.0000, 0.0000)$

This result is interpreted as the appropriate vessel speed for tankers associated with *"OC=normal cost"*, *"BP=low"*, *"Em=less contribution"*, *"Ec=booming"*, "*SD=increase*" and *"SS=increase"* is (*1.0000, full speed*) (figure 3).

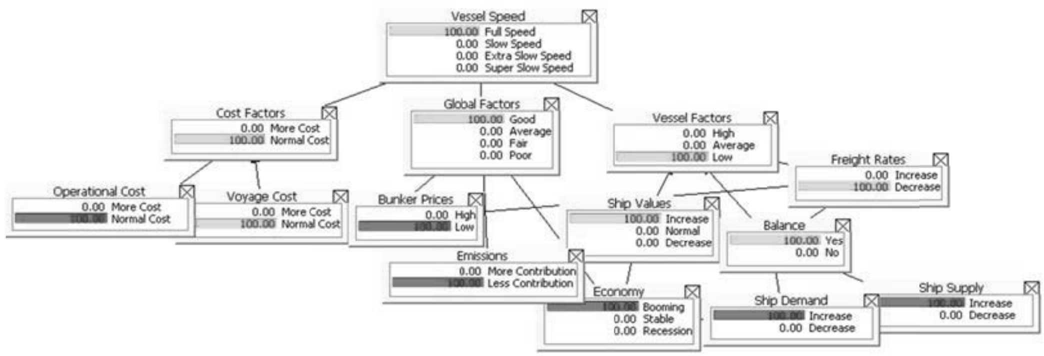

Figure 3: The posterior probability value of the node "*VS=full speed*" after giving evidence to the nodes "OC", "BP", "Em", "Ec", "SD" and "SS"

The same calculation process described in the above situation is applied together with the *Hugin* software tool for analysing the uncertain situations in the tanker shipping industry. Figure 4 illustrates six situations that have occurred simultaneously. If *"OC=normal cost"*, *"BP=low"*, *"Em=less contribution"*, *"Ec=booming"*, "*SD=increase*" and *"SS=increase"* occurred, then the proposed model has suggested a super slow speed must be adopted 100% in operating the tankers.

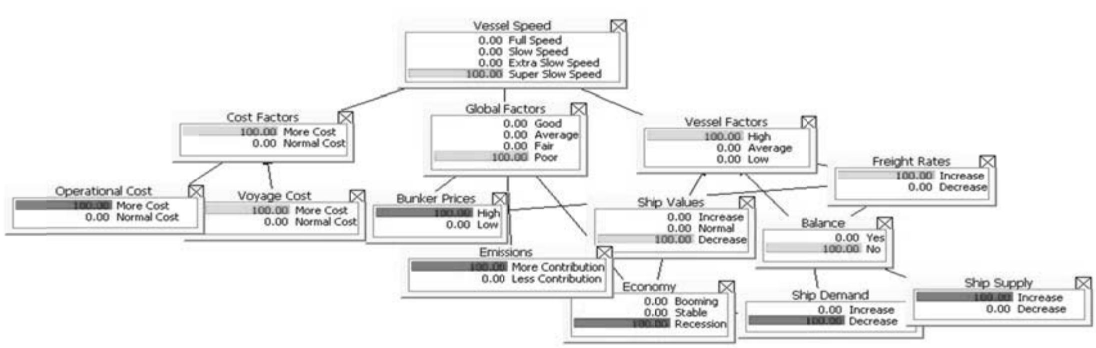

Figure 4:The posterior probability value of the node "*VS=super slow speed*" after giving evidence to the nodes "OC", "BP", "Em", "Ec", "SD" and "SS"

In some situations faced by shipping companies, the six issues did not occur simultaneously. For example, If "*BP=high*", "*Em=less contribution*" and "*Ec=stable*", then the probability values of the node "VS" are *{(0.2544, full speed (VS1)), (0.3015, slow speed (VS2)), (0.2254, extra slow speed (VS3)), (0.2187, super slow speed (VS4))*. It can be concluded that the appropriate vessel speed for operating tankers in such a condition is (*0.3015, slow speed (VS2)*). Such probability values can also be calculated using the *Hugin* software as shown in figure 5.

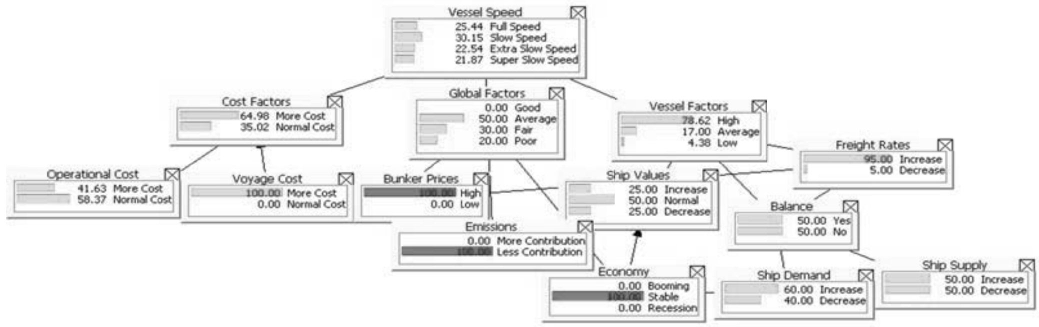

Figure 5: The posterior probability value of the node "*VS= slow speed*" after giving evidence to the nodes "BP", "Em" and "Ec"

Step 5. Results and Discussion

Finally, the proposed model has produced 96 rules. Referring to each rule in table 4, a state under the node "VS" with a posterior probability value higher than others will be chosen as an appropriate vessel speed in operating tankers. Giving Rule 5 as an example, the appropriate vessel speed associated with *"OC=more cost"*, *"BP=high"*, *"Em=more contribution"*, *"Ec=stable"*, "*SD=increase*" and *"SS=increase"* is *{(*0.0872, *full speed (VS1)), (*0.1948*, slow speed (VS2)), (*0.3559*, extra slow speed (VS3)), (*0.3621*, super slow speed (VS4))*is partially shown in table 4. In this situation, it clearly shows that the highest posterior probability value is "*0.3621*, *super slow speed*" compared to the other three speeds. As a result, the decision of choosing a particular steam mode is straight forward and easily understood by shipping companies. All rules in table 4 can be explained in a similar way as Rule 5.

The implications of this research for the maritime industry are as follows 1) the outcome can be used by shipping companies to determine the appropriate vessel speed to be used in a dynamic operational environment and 2) the proposed model is a live decision making model that is assisting shipping companies with their decision making process. In reality, the policy implications that can be deduced from the analysis are that by selecting the right vessel speed, shipping companies are able to control and monitor their shipping business and financial performance by incorporating a number of the parameters described in the proposed model. Furthermore, a low steaming speed helped the tanker shipping industry stay active during the global economic recession, the global financial crisis and also whilst bunker fuel price was increasing. Also, the amendment MARPOL policy concerning the emission standard introduced by the International Maritime Organization (IMO) can be followed by the shipping company without fail.

Table 4: The partial results with a belief structure for analysing the vessel speed

Rules	Antecedent Attributes						Vessel Speed			
No	OC	BC	EM	EC	SD	SS	FS	SS	ESS	SSS
1	more cost	high	more contri.	booming	increase	increase	0.1350	0.3040	0.4360	0.1250
2	more cost	high	more contri.	booming	increase	decrease	0.2250	0.3400	0.3350	0.1000
3	more cost	high	more contri.	booming	decrease	increase	0.2250	0.3400	0.3350	0.1000
4	more cost	high	more contri.	booming	decrease	decrease	0.1350	0.3040	0.4360	0.1250
5	more cost	high	more contri.	stable	increase	increase	0.0872	0.1948	0.3559	0.3621
6	more cost	high	more contri.	stable	increase	decrease	0.1094	0.2125	0.3312	0.3469
7	more cost	high	more contri.	stable	decrease	increase	0.1094	0.2125	0.3312	0.3469
8	more cost	high	more contri.	stable	decrease	decrease	0.0872	0.1948	0.3559	0.3621
9	more cost	high	more contri.	recession	increase	increase	0.0000	0.0000	0.0460	0.9540
10	more cost	high	more contri.	recession	increase	decrease	0.0000	0.0000	0.0000	1.0000
11	more cost	high	more contri.	recession	decrease	increase	0.0000	0.0000	0.0000	1.0000
12	more cost	high	more contri.	recession	decrease	decrease	0.0000	0.0000	0.0460	0.9540
...	...	...	...	...	...	...	...	...	...	...
92	normal cost	low	less contri.	stable	decrease	decrease	0.7875	0.1575	0.0550	0.0000
93	normal cost	low	less contri.	recession	increase	increase	0.0000	0.4400	0.5600	0.0000
94	normal cost	low	less contri.	recession	increase	decrease	0.0800	0.5960	0.3240	0.0000
95	normal cost	low	less contri.	recession	decrease	increase	0.0800	0.5960	0.3240	0.0000
96	normal cost	low	less contri.	recession	decrease	decrease	0.0000	0.4400	0.5600	0.0000

As far as the industry is concerned, by reducing 20% of the vessel speed, it enables the shipping company to save up to 20-30% of the bunker cost. If the bunker cost accounts for 40% of the total voyage cost, then, when the bunker fuel price is high, huge savings can be achieved. Thus, it helps the shipping company to earn more profit and incur fewer expenses when selecting the slow steaming speed.

V. Conclusion

The paper contributes to literature in this field, since the study of the tanker steaming speed in uncertain conditions is fully conducted using a Rule-based Bayesian Reasoning method. The proposed method is considered new in the tanker industry, although it has been wisely applied in other fields such as engineering, risk assessment and human error studies. A test case has been created in this paper with the purpose of demonstrating the proposed model when dealing with the general uncertain situations faced by shipping companies. The developed model is dynamic and is able to be used in different situations based on the uncertain situations faced by shipping companies. In reality, the selection of parameters can be improved upon from time to time based on uncertain situations faced by shipping companies. The output may be different if 1) different situations are adopted, 2) the total number of experts is no less than three, 3) different vessel characteristics are studied and different inputs are included.

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