

RESEARCH ARTICLE

Bayesian belief network model for quantifying the delay risk of marine construction projects in developing countries

Sema Comu¹, Rasa Moeini¹, Ozan Elibol¹, Jiayu Chen²

¹ Bogazici University, Department. of Civil Engineering, Istanbul, Turkiye

² Tsinghua University, Department of Construction Management, Beijing, China

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Abstract

The majority of international trade in goods is carried by maritime transport with higher volume for developing countries. Therefore, considering the enormous contribution of marine construction projects to economic growth, they have become one of the most crucial construction types in many countries. For this reason, the completion of these projects on time has critical importance on the local economy. However, marine construction poses serious risks compared to other construction works, resulting in possible delays since they have significant differences in design and construction. As a result, delay factors identified for different construction projects cannot be transferred directly to marine projects. This study identifies significant delay factors encountered specific to marine construction projects, a crucial gap in the literature. Subsequently, their relationships are examined and approved by experts. We also proposed a Bayesian Belief Network predictive model for estimating schedule delays in the marine project, carried out by a case study. The results show that the delay duration can be predicted using the proposed model before the marine project starts. Also, the identification of dependencies between the delay factors has practical advantages. Practitioners could define the cause-effect relations and prevent delays by focusing on the origins of the delay factors unique to developing countries.

1. Introduction

The marine industry has always been an essential part of international trade and transportation. Every country in the world benefits from the maritime industry, whether the sea surrounds it or not. Since nations are not entirely self-sufficient, they have trade relations with other countries to sell and buy goods and services. Reports in recent years state that over 80% of global merchandise trade by volume, and nearly 70% by value, is handled by maritime transport [1–3]. In developed countries,

the marine industry has a significant impact on GDP. For example, the USA's marine cargo activity generated approximately \$5.4 trillion in total economic activity, accounting for nearly 26% of the nation's GDP [4]. The maritime sector directly contributed over £47 billion in business turnover, £17 billion in Gross Value Added (GVA), and 220,100 jobs to the UK's economy in 2017 [5]. The significant contribution of the marine industry to the economy is not limited to developed countries. According to the report published by the United Nations, 58.8% of exports and 64.5% of imports of

Correspondence Sema Comu  semra.comu@boun.edu.tr

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worldwide maritime trade are allocated to developing countries. Even though, the growth in maritime trade stopped in 2019 with the emergence of Covid-19, which severely affected both local and global economies. It has already started recovering and grow as much as 4.8% in 2021 [3]. Indeed, the marine industry is still regarded as the primary means of global trade; therefore, investment and progress in this sector are critical factors for sustainable development. Low-cost and efficient maritime trade is also of great importance for developing countries. Especially for countries surrounded by water, marine construction projects are extremely important in the local economy. The successful and timely completion of marine construction projects is essential for the immediate economic contribution of the maritime sector. In other words, investors may obtain higher profits by completing the construction on time. Besides the increasing number of investments in marine projects, the construction of marine projects contains more uncertainties, more significant risks, and complex structures than the other construction project types. Risks are inevitable; therefore, a systematic approach is required to identify the root causes of risks in order to minimize adverse consequences or avoid them [6,7]. In this paper, after identifying risk factors, a BBN model is proposed to quantify the effects of delay factors on the schedule overrun and predict the completion time so construction managers can apply the necessary changes and take control of the risks in advance.

2. Literature review

In general, a delay means not completing the project within a specific time agreed upon in a contract because of some factors affecting the project [8]. Researchers investigated the sources of delays in various projects from different perspectives such as project type, contract type, and even considering the perception of multiple stakeholders. For example, in a construction project, the contractor perceives delay as higher overhead, material, and labor costs due to extended work periods and inflation. On the other hand, a delay means a loss of revenue in the

eyes of the owner or client [8]. Researchers show that similar delay factors are generally more critical in developing countries, and these factors have not changed much in the last decade. Accordingly, stakeholder-related factors and financial-related factors are often ranked highest among significant delay factors. While stakeholder-related factors mainly include bad contractor experience, improper contract planning, and multiple change orders by the owner, financial-related factors consist of the owner's financial difficulties and delay in payments [9–13]. Stakeholders can sometimes have different views on the importance and ranking of delay factors. Researchers also stated that although the factors mentioned above are generally regarded as the top delay causes, disagreement among the stakeholders results in a blame culture as well as a shifting of responsibilities and risks [14,15]. In developed countries, nevertheless, the prominent delay factors can be different. For example, according to the respondents from Republic of Korea and Japan, 'Frequent interruptions from the public' and 'Changed site condition' are among the top delay factors [16]. Zidane and Andersen [13] found that poor planning, slow decision-making, and bureaucracy within project organizations are among the top delay factors in the Norwegian construction industry. These are similar to stakeholder-related factors found in developing countries; however, financial-related factors are not reported as the dominant causes of delay. Agyekum-Mensah and Knight [17] used a qualitative approach in addition to literature review and undertook 41 interviews with construction professionals from the UK to come up with fresh insight about causes of delay. They stated that some causes such as insufficient planning and poor project management are consistent with the reported delay factors in the literature and can be regarded as universal delay causes; however, there are also some causes that hard to find in previous studies as they may be specific to a country and/or era.

While many studies analyzed sources of delays in building constructions, several researchers also studied more complex projects. For example,

Kaliba et al. [18] and Khair et al. [19] examined delay factors for road construction projects in Zambia and Sudan, respectively. Namazian et al. [12] studied Iran's gas field development project. Rachid et al. [20] identified the main causes of schedule delay in large construction projects such as highways and dams in Algeria. Delayed payments and financial problems were always reported among the top delay factors in these large-scale infrastructure projects. Many studies frequently mention the shortage of resources and ineffective planning as the other critical delay factors. Besides, Budayan [21], and Yang et al. [22] evaluated delay causes of projects that were delivered under Build-Operate-Transfer (BOT) method in Turkey and Taiwan, respectively. Both studies suggested that uncertainties on political and governmental issues and improper planning are the most significant causes in BOT projects.

On the other hand, marine construction projects and their time and cost overruns have not been studied thoroughly, although these projects significantly impact a country's economy. A Delay in the completion of marine projects is equal to undergoing huge losses. Hence, it is vital to predict and estimate the probable time overrun of the construction. Tam and Shen [23] highlight the need for systematic risk management approaches that can assist both clients and contractors to control risks and to reduce potential losses in marine construction projects as they are exposed to severe risks compared to other types of construction. Marine construction has unique characteristics, and high risks cannot be avoided. Vilvenanthan and Kalidindi's [24] studied causes of delay in utility relocations in road and bridge construction projects. They found that top delay factors would differ from regular construction projects due to many uncertainties and challenging activities. In their study, the top factors included i) lack of information on underground utilities, ii) slow response from utility agencies, and iii) conflict between agencies. In marine projects, particular kinds of equipment are also required because most of the work is done underwater. Engineering principles for marine construction also differ from land-based structures;

therefore, specialized techniques and construction materials are necessary. Consequently, risk factors in marine projects should be evaluated separately, considering their different frequencies and effects.

After identifying risk factors, researchers have implemented various methods besides traditional statistical techniques to analyze their data, find relationships between variables, and estimate time and cost overruns in construction projects. For example, Zeng et al. [25] proposed using a fuzzy analytical hierarchy process (AHP) to prioritize risk factors and deal with uncertainties in the steel erection process of a shopping center construction. Sadeghi et al. [26] also utilized a fuzzy approach to handle uncertainties regarding subjective and linguistically expressed information; however, they combined fuzzy reasoning with Monte Carlo Simulation for risk analysis and proposed a framework that can address both random and fuzzy uncertainties. For verification, they employed their framework to estimate the cost of a highway overpass project. Yang and Ou [27] used a different method to analyze the interrelated dependent relationships among delay factors. They applied Structural Equation Modeling (SEM) to quantify how various factors work together to affect the project schedule. Bayesian Belief Network (BBN) is another method that has recently gained more attention to model the interactions among project risks and predict construction time and cost performance. For example, Luu et al. [28] and Namazian and Yakhchali [12] applied BBN to model complex relationships in projects and analyze effects of risks on the distribution of other factors. The method is also useful for implementing expert judgments to build conditional probabilities among the risks in order to quantify the likelihood of schedule delay in the construction sector. BBN is an effective method, and multiple studies adopted this method to analyze risks in various operations such as drilling [29] and gas station safety [30].

Regarding the maritime industry, it is possible to find multiple studies that have analyzed risk factors, particularly risks related to marine transportation and offshore safety [31–34]. However, the literature lacks enough studies

explicitly dealing with delay factors in marine construction projects; therefore, it is necessary to analyze these risk factors, specifically those encountered only in developing countries. This study aims to fill a crucial gap in the literature by identifying the delay factors through extensive literature review and expert opinion and analyzing their relationships.

3. Research methodology

Marine construction poses serious risks compared to other construction works, resulting in possible delays since they have significant differences in design and construction. First of all, besides ground conditions, designers should also consider data on waves, currents, and sea transportation. Moreover, since most of the construction work is done underwater, it requires specially trained divers and sophisticated equipment. In summary, the engineering and construction principles are different in marine projects; hence some requirements are not commonly used in general construction projects. As a result, delay factors identified for other types of construction projects cannot be transferred directly to marine projects. For this reason, we initially identified delay factors unique to marine construction projects in developing countries through an extensive literature review. Table 1 presents all the previous studies from various countries that have been used for this purpose. Although there are many studies in the literature on construction delay factors, most of them indicate similar factors. Accordingly, we combined or eliminated some of the delay factors. Moreover, only very few studies are related to the delay factors of marine projects; studies often examine other types of construction projects, e.g., building construction, in various countries. For this reason, the final delay factor list specific to marine construction projects is approved by a focus group consisting of two academicians and three experienced professionals from the marine construction industry.

In this study, BBN is chosen as an appropriate method to benefit from the identified risks and their relationships in order to introduce a model to

predict the schedule delay in marine construction projects. BBN offers distinct advantages in comparison to other probabilistic methods for several reasons. It excels at capturing and representing complex interdependencies and interrelations among variables. In addition, BBN offers transparency and interpretability, which are highly valuable in risk analysis and decision-making contexts. The graphical nature of BBN facilitates the communication and understanding of complex relationships among risk factors, aiding in identifying critical variables and assessing their impacts. Finally, it provides a robust framework for modeling and reasoning under uncertainty. Construction delay risk involves multiple sources of uncertainty, such as incomplete data, varying project conditions, and evolving risk factors. A BBN accommodates these uncertainties by explicitly incorporating probabilistic information and allowing for updating beliefs based on new evidence.

3.1. Data collection

A standard method to gather industry-specific and reliable data is to prepare and distribute questionnaires to the experts who have credentials to provide the required data for the study. For this research, we designed two sets of questionnaires. The first questionnaire was distributed to a random sample of construction professionals who have experience in marine construction projects in developing countries. It is important to note that we did not send the first questionnaire to people working on the case study project. On the other hand, the second questionnaire was only distributed to the case study's professionals for validation purposes. The first questionnaire consists of three main sections. We designed the first part of the questionnaire to gather participants' demographic information (e.g., work experience and occupation title) and information about the projects that participants had worked on (e.g., project delivery method and contract type). In the second part, the questionnaire focuses on the amount of schedule delay and its results on a marine construction project.

Table 1. List of previous studies used to review and identify the major delay factors

Country	Delay Factors	Categories (groups)	Type of Project	References
Algeria	59	9	Infrastructure	[20]
Cambodia	31	5	Residential Building	[35]
Egypt	32	9	Building	[14]
Egypt	31	5	Building and Infrastructure	[10]
Ghana	32	9	Building	[36]
Ghana	26	-	Groundwater Projects	[37]
Hong Kong	18	6	Marine Construction	[23]
India	48	-	Road and Highway	[38]
India	20	2	Road and Bridge	[24]
Iran	20	4	Gas Field Development	[12]
Iran	28	8	Building and Infrastructure	[39]
Jordan	40	8	Residential Building	[40]
Jordan	28	8	Large Scale PPP	[41]
Korea	27	5	Building and Infrastructure	[16]
Malaysia	28	8	Building and Infrastructure	[42]
Morocco	49	9	Building and Infrastructure	[9]
Oman	44	4	Infrastructure	[15]
Pakistan	53	9	Building and Infrastructure	[11]
Saudi Arabia	73	9	Large Scale PPP	[8]
Sudan	66	6	Road and Highway	[19]
Taiwan	80	8	PPP (BOT)	[22]
Turkey	83	9	Building and Infrastructure	[43]
Turkey	34	7	Building and Infrastructure	[44]
Turkey	59	8	PPP (BOT)	[21]
UK	32	15	Building and Infrastructure	[17]
Universal	113	18	Building and Infrastructure	[45]
Universal	33	-	Building and Infrastructure	[13]
Vietnam	16	9	Building	[28]
Zambia	14	3	Road and Highway	[18]

More specifically, we asked about the duration of the project activities and the percentage of the schedule delay concerning the duration specified in the contract. We also asked about the impact of the schedule delay in marine construction projects to understand the possible effects on the project's success. The third and most important part of the

questionnaire aims to gather the frequencies of the delay factors, which can be encountered in a marine construction project. This data constructs the basis of delay factors' marginal probabilities and is utilized to calculate the Pearson Correlation Coefficient. The correlation among delay factors was calculated in the quantitative analysis part, and

a BBN model was constructed based on factors causing the schedule delay. Finally, the estimated schedule delay was compared with actual data from a case study to validate the model. For this purpose, we collected data from experts who can provide the necessary data about the case study project.

3.2. Calculating pearson correlation coefficient

The strength and direction of the dependencies between two random variables can be determined by calculating their correlation. Multiple correlation coefficient measures have been introduced, and each can be used for a different scenario. As Kwoh and Gillies [46] suggested, Pearson Correlation Coefficient can be used to evaluate the conditional dependencies of variables in a system and may be expressed as follows:

$$\rho_{x,y} = \frac{\text{cov}(x,y)}{\sigma_x \cdot \sigma_y} \quad (1)$$

where *cov* means covariance, and σ_x and σ_y are standard deviations of random variables *x* and *y*, respectively.

Researchers have various suggestions about the interpretation of the Pearson Correlation Coefficient, ρ . Here, to evaluate the strength of ρ describing the relationship between variables, the values recommended by Evans [47] has been used, in which values between 0.00 – 0.19 are considered as very weak; 0.20 – 0.39, weak; 0.40 – 0.59, moderate; 0.60 – 0.79, strong; and 0.80 – 1.00, very strong. In this way, Bayesian Belief Networks can be constructed as the strength of each dependency was obtained quantitatively.

3.3. Bayesian analysis

Bayesian inference is a probabilistic method that combines previously obtained information about a population parameter with the evidence of information contained in a sample. The Bayesian approach is set up on the conditional probability theory, which can be defined as the probability of an event given that another event has occurred or will occur [48]. This statistical approach comprises three main elements; prior belief, likelihood function, and posterior distribution. The prior

distribution presents the prior belief of the analysts, and the likelihood function modifies the prior belief with the currently available data. In the Bayesian approach, parameters are considered as random variables from a prior belief. Subsequently, these parameters are used to update the beliefs in the posterior distribution with the evidence, presenting the quantitative result in a probabilistic manner [49]. The general mathematical equation of the Bayesian approach is based on Bayes' theorem. It is calculated using Eq. 2 as shown below:

$$P(A_i|B) = \frac{P(A_i) \times P(B|A_i)}{\sum_{i=1}^N P(A_i) \times P(B|A_i)} \quad (2)$$

In Eqs. (1), $P(A_i)$ is called the prior distribution or the marginal probability of A_i , $P(B|A_i)$ is the likelihood function showing the probability of *B* given that A_i occurs and $P(A_i|B)$ presents the posterior distribution of A_i when the available data is uploaded to the prior distribution. The Bayesian formula is the basis of the BBN method and is widely used in uncertainty analysis [50]. However, BBN exhibits the graphical distribution of a set of variables and their dependencies in a stochastic system in terms of conditional and posterior probabilities [51]. In the graphical representation, the arrows indicate the causality relationships from observed data or opinions of an experienced professional. Bayesian Networks allow users to observe the conditional dependencies easily. Consequently, analysts can follow the logical sequence in the domain of parameters by reviewing the causal relationships between the variables [52]. In other words, BBN can depict cause and effect relationships through graphical models. A simple cause-effect relationship in a belief network consists of two nodes: parent and child. The parent node represents the cause variable, whereas the child node depicts the affected variable. Also, the dependency arrow shows the direction from the cause variable to the affected variable.

4. Findings

4.1. Respondents profile

We distributed an online questionnaire to 153 experienced professionals in marine construction projects. Of the returned questionnaires, 35 were useable with complete information, representing a response rate of 23%. Respondents were allowed to select more than one choice in identifying their area of expertise and involved organization. Therefore, the sum of the frequencies might exceed the total number of respondents, which is 35. However, they had to select at most one choice in years of experience in marine construction projects. According to the survey, only around 14% of the respondents have more than 20 years of experience, and most have less than 10 years of experience. They are involved in projects, mainly as contractors, designers, or engineers. Table 2 presents the profile of the respondents in greater detail.

Table 2. Respondent profile

Years of Experience in Marine Construction Projects	Frequency	Percent
>20 years	5	14.29%
10-20 years	5	14.29%
<5 years	13	37.14%
6-10 years	12	34.29%
Involved Organization	Frequency	Percent
Owner	8	16.00%
Consultant	7	14.00%
Designer/Engineer	17	34.00%
Contractor	18	36.00%
Area of Expertise	Frequency	Percent
Project Manager	8	13.11%
Contract Manager	2	3.28%
Designer/Engineer	13	21.31%
Resident / Site Engineer	15	24.59%
Quality / Control	5	8.20%
Project Management Officer (Planner, quantity surveyor etc.)	18	29.51%

The collected data also includes information on contract durations and schedule delays of the projects in which respondents have been working. Accordingly, marine construction projects were mainly planned to be completed between 1 and 2 years, and the most encountered delays were less than 6 months. We presented the data collected in Table 3.

In the initial list of delay factors, there were 257 delay factors in 25 different categories. However, after consulting with academicians and professionals in the sector, some of the delay factors that had very close meanings are combined by merging their definitions. For example, one of the delay factors called "lack of experience of stakeholders in marine construction projects" is formed by merging the delay factors such as "lack of experience of the consultant," "lack of experience of the contractor," "lack of experience of the designer," and "lack of experience of the owner." Table 4 presents the 46 delay factors recognized and grouped under 6 categories at the end of this process.

After the factors were identified, the respondents scored the delay factors using the Likert Scale (0= Never, 0.25= Very rarely, 0.5= Occasionally, 0.75= Frequently, and 1= Constantly). Then, we statistically analyzed the ratings and quantified delay factors based on their mean frequency. In addition, the mean frequencies of the categories are ranked as summarized in Table 5.

Table 3. Contract duration and delay

Contractual Duration of the Marine Project	Frequency	Percent
<1 year	6	17.14%
>4 years	1	2.86%
1-2 years	15	42.86%
2-4 years	13	37.14%
Amount of Schedule Delay	Frequency	Percent
<6 months	17	48.57%
>24 months	1	2.86%
6-12 months	14	40.00%
12-24 months	3	8.57%

Table 4. Finalized risk groups and related delay factors

Risk Type	Delay Factors	Mean Frequencies	Rank
Stakeholders related	x1, Lack of experience of stakeholders in marine construction projects	0.564	15
	x2, Conflicts and poor coordination between stakeholders	0.507	24
	x3, Delays in approval processes by consultant or owner	0.564	16
	x4, Inflexibility of consultant	0.507	25
	x5, Frequent change of subcontractors because of their inefficient work	0.479	32
	x6, Improper construction methods implemented by contractor	0.429	37
	x7, Inadequate number of or incompetent project team of contractor	0.429	38
	x8, Poor site management, site work, and supervision by contractor	0.457	36
	x9, Unstable management structure, and style of consultant	0.371	41
	x10, Lack of capable owner representative or management failures of owner side	0.464	34
	x11, Late project commencement of contractor	0.486	30
Resources related	x12, Unstable management structure, and style of contractor	0.464	35
	x13, Equipment allocation problem	0.500	27
	x14, Frequent equipment breakdowns / Failure or improper equipment	0.557	19
	x15, Shortage of resources	0.507	26
	x16, Slow mobilization or slow/late delivery of resources	0.536	22
	x17, Unskilled equipment operators or low worker skills/productivity	0.479	33
	x18, Labor strike	0.164	46
	x19, Changes in material types and specifications construction	0.421	39
	x20, Damage of stored materials	0.243	44
	x21, Quality of materials or improper material selection	0.379	40
	x22, Accidents during construction	0.307	43
Design related	x23, Inaccurate site investigation by consultant	0.514	23
	x24, Complex or impractical project design	0.579	10
	x25, Design changes by owner or his agent during construction	0.657	3
	x26, Design errors and delays made by designers	0.643	4
	x27, Inadequate details in drawings	0.579	11
	x28, Providing site instructions by designer not on time	0.643	5
	x29, Inconsistency between site conditions and design outcomes	0.614	8
	x30, Unexpected surface and subsurface conditions	0.564	17
Externality related	x31, Force majeure	0.371	42
	x32, Unfavorable weather conditions	0.629	6
	x33, Fraudulent practices and corruption	0.214	45
Project Management and Contract related	x34, Contract management	0.571	12
	x35, Ineffective quality assurance/Control	0.543	21
	x36, Unsuccessful project planning and scheduling	0.571	13
	x37, Lack of incentives or penalties for contractor to finish ahead of or behind schedule	0.500	28
	x38, Unrealistic contract durations imposed by client	0.664	1
	x39, Improper type of construction contract or project delivery system (Turnkey, DBB, BOT)	0.486	31
	x40, Type of project bidding and award (negotiation, lowest bidder, ...)	0.629	7
	x41, Improper project feasibility study	0.564	18
Financial related	x42, Difficulties in financing project or cash flow management	0.664	2
	x43, Global financial crisis	0.550	20
	x44, Price fluctuations	0.571	14
	x45, Inflation	0.493	29
	x46, Exchange rate fluctuation	0.593	9

Table 5. Mean frequencies of main categories

Risk Type	Mean Frequencies
Design related	0.60
Financial related	0.57
Project Management and Contract related	0.57
Stakeholders related	0.48
Resources related	0.41
Externality related	0.40

4.2. Correlation between factors

Pearson Correlation Coefficient cannot evaluate which variable is the parent variable (node); therefore, the supervisor of this study and an experienced professional's comments were utilized to understand the direction of the relationship between the variables. For a series of measurements, Pearson Correlation Coefficient can be rewritten as below in Eq. 3 [53]:

$$r(x_i, x_j) = \frac{cov(x_i, x_j)}{\sqrt{var(x_i)var(x_j)}} = \frac{\sum_{k=1}^N (x_i^{(k)} - \bar{x}_i)(x_j^{(k)} - \bar{x}_j)}{\sqrt{\sum_{k=1}^N (x_i^{(k)} - \bar{x}_i)^2} \sqrt{\sum_{k=1}^N (x_j^{(k)} - \bar{x}_j)^2}} \quad (3)$$

Where N is the sample size. $x_i^{(k)}$ and $x_j^{(k)}$ are the individual sample points indexed with k . $\bar{x}_i = \frac{\sum_{k=1}^N x_i^{(k)}}{N}$ denotes the mean value of sample x_i , and analogously for $\bar{x}_j$.

The pairwise calculations were carried out for all variables, and weak relationships were removed and not integrated into the model. According to Evans [47], coefficients with a value less than 0.4 can be considered weak; therefore, only solid relationships were taken into account and presented in Table 6.

4.3. Calculating joint and conditional probabilities for Bayesian belief network model

Based on the data gathered from the questionnaires, we calculated the average and standard deviation values of all the variables and their correlation. With all these values at hand, we obtained the conditional probabilities using a web app developed by Dinov et al. [54]. This online tool lets us calculate the conditional probability between two variables by assuming bivariate normal distributions. Then, we used the conditional probabilities in the model to estimate the probability of occurrence of each delay factor. For nodes, which do not have parent nodes, the probabilities can be entered as their frequencies with the values collected from the respondents. For example, "Global financial crisis (x43)" does not have a parent node, so its frequency, 0.55, is loaded as its joint probability. On the other hand, most nodes have at least one parent node, making the BBN model more complex. Eq. 4 can be utilized when there are one or more parent nodes before a node. Here, the parent nodes are accepted as statistically independent because there is no relation within the parent nodes. Therefore, this equation can be rewritten as Eq. 5 due to the independence of the parent nodes of each other.

$$P(X|A_i, \dots, A_j) = \frac{P(A_i, \dots, A_j|X) \times P(X)}{P(A_i, \dots, A_j)} \quad (4)$$

$$P(X|A_i, \dots, A_j) = \frac{P(A_i|X) \times P(A_{i+1}|X) \times \dots \times P(A_{j-1}|X) \times P(A_j|X) \times P(X)}{P(A_i) \times P(A_{i+1}) \times \dots \times P(A_{j-1}) \times P(A_j)} \quad (5)$$

5. Case study

Another set of data is required to verify the proposed model for estimating the schedule delay of marine constructions. Therefore, a marine construction project in Istanbul, Turkey, was selected as a case study to test the proposed model.

Table 6. Strong dependencies between variables

Factor 1	Factor 2	Correlation	Factor 1	Factor 2	Correlation	Factor 1	Factor 2	Correlation
x22	x20	0.763	x9	x37	0.519	x22	x42	0.455
x46	x45	0.760	x30	x26	0.518	x18	x15	0.451
x8	x6	0.744	x7	x2	0.507	x7	x21	0.445
x26	x28	0.732	x38	x9	0.506	x34	x3	0.440
x17	x16	0.724	x12	x7	0.506	x2	x6	0.440
x27	x29	0.692	x21	x6	0.505	x1	x29	0.438
x45	x44	0.646	x9	x28	0.505	x5	x7	0.434
x1	x7	0.632	x17	x22	0.504	x4	x5	0.434
x34	x39	0.624	x26	x24	0.497	x9	x29	0.423
x28	x35	0.608	x24	x27	0.495	x23	x24	0.422
x36	x25	0.589	x41	x39	0.488	x1	x17	0.422
x16	x15	0.582	x29	x35	0.486	x36	x17	0.420
x39	x25	0.571	x14	x42	0.478	x34	x36	0.416
x17	x20	0.542	x14	x15	0.470	x22	x15	0.412
x31	x32	0.537	x25	x26	0.465	x45	x18	0.409
x33	x35	0.536	x36	x21	0.463	x32	x14	0.406
x12	x11	0.534	x44	x42	0.461	x42	x18	0.405
x2	x8	0.533	x43	x46	0.459	x41	x40	0.403
x10	x2	0.527	x42	x19	0.459	x12	x14	0.402
x10	x9	0.522	x15	x13	0.455	x3	x28	0.400

Turkey has a developing economy and, due to its geography, has a high potential for maritime investments. The coastline of Anatolia is more than 8000 km long, and international trade is mainly realized through maritime transportation. The number of ports and shipyards has been increased through the years, and because of Turkey's strategic location, large-scale investments are still being realized in this sector [55]. For this reason, many marine construction projects are initiated by the public and private sector or by their partnerships to increase the number of facilities and their contribution to the local economy in Turkey. The chosen project is a good representation of these investments, especially regarding the evaluation of delay factors during construction, as it can have subsequent effects on maritime economics. The project started in February 2013, and according to

the contractual agreement, the construction period was planned as 24 months. However, the construction period of this project was extended to 30 months, meaning that the length of the schedule delay is 6 months. In other words, the project was exposed to a 25% schedule delay compared to the contract duration assigned by the owner in the contract signed with the contractor. Researchers sent ten additional and modified questionnaires to the professionals working in this case study project to analyze the delay causes. The difference between the previous questionnaire and the modified questionnaire is the number of delay causes. In the revised version of the questionnaire, only the 12 delay causes that do not have parent nodes are presented to the respondents, and they evaluated the delay causes in terms of their frequencies. When the joint probabilities of these 12 delay factors are

changed, the behavior of the remaining delay causes will be automatically updated since the conditional probabilities are already known in the model. The respondents from the case study project evaluated the delay causes, and Table 7 shows the average frequencies of case study delay factors.

5.1. Building the BBN model

A computerized model is needed to represent the complex network of delay factors and their dependencies. For this study, MSBNx, a free Windows application from Microsoft Inc., is selected to create and evaluate the BBN model [56]. In the first step, all the nodes that represent the delay causes are placed into the model. Then, the dependencies between the nodes are defined according to the cause-effect relationships. The arcs are drawn from the parent node to a child node to represent the dependencies. It is accepted that the delay factors that do not have child nodes will become the parent nodes of the 'Delay' variable, which is the resultant variable of all other variables. The 'Delay' variable ended up having eight parent nodes after the network is built and relationships are defined. After creating the model, each node must be separately considered in terms of their joint and conditional probabilities. Finally, observations are entered into the model to evaluate the resultant

frequencies of each node. In MSBNx, observations (evidence) are imported as either "observed" or "not observed" because the software application does not allow the users to load the observed data as frequencies. For this reason, frequencies larger than 0.5 are accepted as "observed" delay factors, and the remaining factors are inserted into the model as "not observed" delay causes (Table 7). Luu et al. [28] suggested that each variable in the model must have four characteristics; 1) name, 2) status, 3) its relationship and connection with other variables, and 4) a data table containing joint and conditional probabilities. An essential step in building the BBN is determining a node's status because it reflects the behavior of that node. For example, each node representing delay causes has two states; "Yes" or "No"; the former indicates the probability of occurrence of that node, whereas the latter shows the opposite. However, the status of 'Delay' is different from the other nodes. It has the following three states: '<33%', '33%-66%', and '>66%'. These states represent the duration of the time overrun compared to the contractual time for completion. This kind of division of schedule delay into three equal states is mainly due to schedule delays from similar projects in the region (Table 3), and experts in the field also advised it.

Table 7. Mean of frequencies of delay factors in the modified questionnaire

Delay Factors (Parent Nodes)	Mean of Frequency	Observed?
x1, Lack of experience of stakeholders in marine construction projects	0.73	Yes
x4, Inflexibility of consultant	0.55	Yes
x10, Lack of capable owner representative or management failures of owner side	0.43	No
x12, Unstable management structure, and style of contractor	0.38	No
x23, Inaccurate site investigation by consultant	0.65	Yes
x30, Unexpected surface and subsurface conditions	0.63	Yes
x31, Force majeure	0.30	No
x33, Fraudulent practices, and corruption	0.28	No
x34, Contract management	0.56	Yes
x38, Unrealistic contract durations imposed by the client	0.63	Yes
x41, Improper project feasibility study	0.40	No
x43, Global financial crisis	0.40	No

The most critical step while building the model is entering the data into the joint probability and conditional probability tables. The probability table is filled by the frequency data gathered from the first set of questionnaires for the nodes, which do not have a parent node. As for the remaining nodes, the probability of occurrence of each child node is calculated using Eqs. (3) and then entered into the model. Fig. 1 is an example representing conditional probabilities of "Labor strike" (x18) that has two parent nodes, "Difficulties in financing project or cash flow management (x42)", and "Inflation (x45)". The conditional probabilities of "Labor strike (x18)" given that both the mentioned variables occur can be calculated with the simplified formula using Eqs. 6-8:

$$P(x_{42}|x_{18}) = 0.978 \quad (6)$$

$$P(x_{45}|x_{18}) = 0.979 \quad (7)$$

Parent Node(s)		X18		
X42	X45	Yes	No	bar charts
Yes	Yes	0.48	0.52	
	No	0.01	0.99	
No	Yes	0.021	0.979	
	No	0.0004	0.9996	

Fig. 1. Sample table for conditional probabilities of a delay factor

$$P(x_{18}|x_{42}, x_{45}) = \frac{0.978 \times 0.979 \times 0.16}{0.66 \times 0.49} = 0.48 \quad (8)$$

5.2. Model output and evaluation of result

Once the model is developed, observations of the case study must be entered into the model. After all the observations from the case study are entered into the model as evidence, MSBNx facilitates the data, and the probabilities of all nodes are automatically updated (Fig. 2).

Based on the model indicated in Fig. 2, the likelihood of the delay in the case study project is shown in Table 8. It represents an acceptable estimation of the quantity of the delay as the project experienced a 25% schedule delay in the actual case.

Table 8. Likelihood of schedule delay

States	Likelihood of Delay
<33%	57%
>33% and <66%	23%
>66%	20%

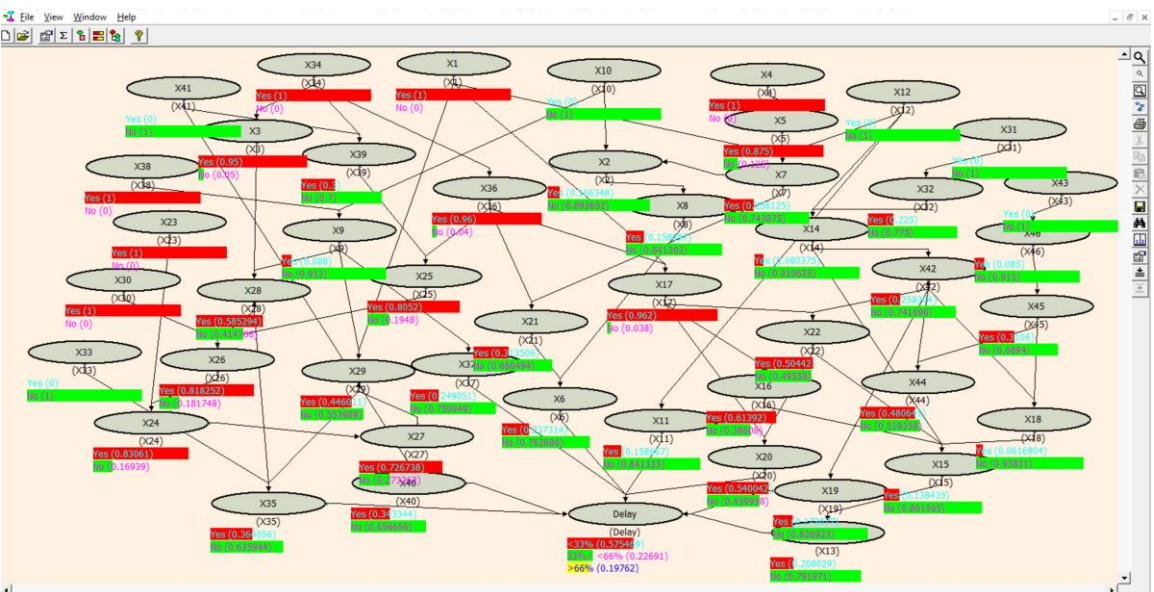


Fig. 2. Overview figure of the BBN model with updated probabilities

6. Discussion

This study initially identifies and categorizes the delay factors encountered in marine projects and then examines their frequencies. There are multiple reasons why studies in the literature list different delay factors and categorizations. The factors are sensitive to country, project type, time of construction, and they can also vary depending on the perception of different stakeholders. For example, Kaliba et al. [18] identify only 14 delay factors under three categories after analyzing risks in road construction projects in Zambia. On the other hand, another study conducted by Ramanathan et al. [45] is an example of a non-specific categorization. They list 113 delay factors under 18 categories as their work results from analyzing studies from different countries and multiple project types. The time of the construction and when a study was conducted are also critical and should be considered. Even in a specific country and considering similar project types, studies from different years may not be entirely comparable as social, economic, and cultural settings can change over time [57]. Furthermore, the perspective of researchers can affect the list of delay causes [39]. Studies can focus on the perception of a single stakeholder and analyze a project through their eyes or consider all the stakeholders' views. For example, Tam and Shen [23] analyzed delay causes in marine projects from the contractor parties' perspective. However, this study contributes to the literature by presenting the probable delay factors in marine construction projects in developing countries not only from the contractors' view but also from the views of all the stakeholders.

Although the findings of this study are similar to studies on delay factors in general construction projects in developing countries, the differences stem from the distinctive characteristics of marine projects. As stated before, marine projects contain more uncertainties, higher risks, less technically skilled professionals, and more unnecessary bureaucratic processes. In addition, they are more subject to seasonal impacts when compared with the other types of construction projects. The results

of Tam and Shen's [23] marine project study, conducted in Hong Kong, show that the most commonly encountered risk factor is "underwater conditions being different from tender assumptions." However, in our study, we found "unrealistic contract durations imposed by the client" and "difficulties in financing project or cash flow management" as the most frequent delay factors. The delay factors that we identified are more similar to the top delay factors in construction projects specific to developing countries than their findings in the study of marine projects in a developed country. Therefore, it is important whether the research is conducted for developed or developing countries and for which stakeholders the risk factors are evaluated. Also, it must be noted that the top two significant factors do not belong to the most significant delay category, which is Design-related. However, the following three dominant factors are all associated with design errors and changes. Our rankings are based on average values, which explains the discrepancy between top risk factors and top categories.

Study results suggest that the developed BBN model can accurately predict the schedule delay within the specified limits. This method is a proper choice for the estimation of schedule delay. According to Weber et al. [58], BBN models are widely utilized for risk analyses as they can quantify low probability events but with high consequence effects. There is also an increasing trend in BBN application due to various benefits over other classical methods and its user-friendly graphical approach. Graphical representation makes the developed model easily adopted by practitioners. It allows them to modify the model according to the project at hand and monitor each factor's effect on the final schedule delay. Regarding the schedule delay factor in the model, other researchers have considered different values as states of the delay depending on projects at hand and their expert panel validation. For example, Luu et al. [28] divided the delay factor into three parts: "less than 10%", "between 10% and 20%", and "greater than 20%". The two case studies they had analyzed had 7.7% and 12.5% time overrun

compared with completion time based on contract, and they needed to differentiate if the delay is less or greater than 10%. Wang et al. [59] had the same reasoning in their division of delay ratio, although they came up with a different categorization. It is comprised of minor delay (≤ 0.1), moderate delay ($0.1 < \text{and} \leq 0.5$) and severe delay (> 0.5). However, in our case and most of the projects in the region, schedule delay is about 25%-30% and some other more than even 50% of the original contract time; therefore, the division of states into three equal parts (33%) seems appropriate.

This study has some limitations as well. The first limitation is the number of respondents to the questionnaire surveys, 35 respondents with a response rate of 23%. Receiving more responses and collecting more information provides a better chance to analyze the data in greater detail. Another limitation is related to the number of case studies. Applying this model for other case studies may not result in very accurate estimations like this project, and some deviations in schedule delay calculations can be seen. Therefore, further case studies can be conducted to evaluate and validate the proposed model in greater detail. In order to build the BBN model, we made some assumptions to come up with a simple yet proper and accurate model. These assumptions decrease the complexity of the model and may lead to results that differ from real-life consequences. The first assumption was that factors have bivariate normal distributions to calculate conditional probabilities based on their correlation, averages, and standard deviations. Another simplification is related to evaluating the 12 main risk factors without parent nodes as "observed" or "not observed" based on their mean frequencies gathered from questionnaires. Values greater than 50% are recognized as "observed"; this is not entirely accurate. More data is needed to do statistical analysis and utilize real observations into the model as these prior observations significantly impact the final results. Future research may also explore sophisticated relationships among delay factors and build a more complex network. Researchers can also integrate risk management and mitigation strategies into BBN models and

analyze the effects of different scenarios on each risk factor and the general risk model. Future research can use sensitivity analysis to investigate the risks that have significantly influenced project delays. In a Bayesian network, sensitivity analysis aims to understand how changes in the input variables' values or distributions affect the posterior probability and predictions. It also helps to learn more about the model's stability and robustness and, if necessary, adjust the model's structure or parameters. Nevertheless, it is again necessary to gather sufficient data that is accurate and reliable and then use them as the foundation of a complex BBN model.

7. Conclusion

The marine construction projects are one of the fastest-growing industries in developing countries, and with each new investment, they are adding more contribution to the local economies. To fulfill the demands of this growing industry, the issues related to the delay factors that prevent these projects from being completed on time are gaining great significance. Estimating the probable delay in completing these projects is essential for adequately managing the construction phase, providing the necessary risk responses, and minimizing the losses. However, studies regarding the time overrun prediction in marine construction projects in developing countries are limited. Therefore, this study aims to achieve the following objectives: identification and categorization of the delay factors encountered in the marine construction industry; the degree of dependencies between the delay factors; and finally, to come up with a model to predict the schedule delay with acceptable accuracy in a marine project in Turkey by utilizing the proposed BBN model. After a thorough literature review and experts' help, previously identified delay factors were merged and, in some cases, eliminated. This process was done depending on whether they were relevant to marine projects in developing countries or not. Consequently, this study presents a list of delay factors and their rankings according to their frequencies. Since most of the factors are interrelated, we found quantitative

relationships between factors by utilizing the pairwise calculations of Pearson Correlation Coefficients. After defining the relationships, we built the BBN to draw the path causing delay, and we integrated the conditional probabilities into the model. The proposed model makes accurate estimations; therefore, the delay duration of an uninitiated marine project can be estimated by utilizing this tested model with minor modifications. Moreover, this study presents practical contributions to project managers working in marine projects. They can benefit from the proposed model to identify the probable delay factors and define cause-effect relations. Thus, by focusing on the root cause of the delay factors, they may minimize or prevent the schedule delay.

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Author Contributions

S. Çomu: Conceptualization, Methodology, Writing-Review & Editing, Supervision, Project Administration; R. Moeini: Formal Analysis, Data Curation, Writing-Review & Editing; O. Elibol: Formal Analysis, Investigation, Resources, Writing-Original Draft, Visualization; J. Chen: Supervision, Writing-Review & Editing.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Ethics Committee Permission

The authors acquired ethics committee permission for surveys implemented in this paper from the Science and Engineering Fields Human Subjects Ethics Committee of Boğaziçi University (Date: 11.04.2023; No. E-84391427-050.01.04-122031).

Conflict of Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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