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Bayesian Network Models for Evaluating the Impact of Safety Measures Compliance on Reducing Accidents in the Construction Industry

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Abstract: Construction is one of the most hazardous industries worldwide. Implementing safety regulations is the responsibility of all parties involved in a construction project and must be performed systematically and synergistically to maximize safety performance and reduce accidents. This study aims to examine the level of safety compliance of construction personnel (i.e., top management, frontline supervisors, safety coordinators/managers, and workers) to gain insight into the top safety measures that lead to no major or frequent accidents and to predict the likelihood of having a construction site free of major or frequent accidents. To achieve the objectives, five safety measures subsets were collected and modeled using six combinations of five different Bayesian networks (BNs). The performance of these model classifiers was compared in terms of accuracy, sensitivity, specificity, recall, precision, F-measure, and area under the receiver operating characteristic curve. Then, the best model for each data subset was adopted. The inference was then performed to identify the probability of the commitment to safety measures to reduce major or frequent accidents and recommend enhancement regulations and practices. While the context in this paper is the Jordanian construction industry, the novelty of the work lies in the BN modeling methodology and recommendations that any country can adopt for evaluating the safety performance of its construction industry. This research endeavor is, therefore, a significant step toward providing knowledge about the top safety measures associated with reducing accidents and establishing efficiency comparison benchmarks for improving safety performance.

Keywords: construction safety; Bayesian network; safety performance; accidents occurrence

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Citation: Al-Kasasbeh, M.; Mujalli, R.O.; Abudayyeh, O.; Liu, H.; Altalhoni, A. Bayesian Network Models for Evaluating the Impact of Safety Measures Compliance on Reducing Accidents in the Construction Industry. *Buildings* **2022**, *12*, 1980. https://doi.org/10.3390/buildings12111980

Academic Editor: Annie Guerriero

Received: 21 October 2022
Accepted: 11 November 2022
Published: 15 November 2022

1. Introduction

Construction is one of the most hazardous industries, with the highest rates of injuries and fatalities worldwide [1–3]. According to the department of statistics, the construction industry in Jordan is approximately 3.7% of the Gross Domestic Product (GDP) [4]. However, it is considered a dangerous work environment with workers exposed to various types of hazards, including hazardous materials, harmful equipment, toxic chemicals, and continuous noise. These types of hazards can result in injuries that are severe and permanent. They can also lead to psychological disorders such as panic, fear, and the inability to reason rationally and accurately [2,5,6].

Jordan's economy has suffered human and financial losses due to poor safety management in the construction industry [7]. According to the Social Security Corporation (SSC), the construction industry contributed to 5.5% of all workplace accidents in 2019 [8]. One simple accident can result in a financial loss of 520 Jordanian dinars, equal to around $740, and a minimum of one week of leave for the injured laborer/s (Sarireh 2014). The fatal injury incidence rate in the Jordanian construction industry was 13.9 per 100,000 workers in 2019 [8]. It was much higher than the fatal injuries rates of the United Kingdom

(UK) and United States (US) construction industries, which were equal to 1.6 and 9.7 per 100,000 workers for the same year, respectively [9,10]. Therefore, there is a dire need to pay more attention to occupational safety in the Jordanian construction industry. However, safety should not only be viewed as regulations that must be adhered to but also become a value and a culture with a clear commitment from all levels of the construction workforce [3].

Several studies breakdown the construction company workforce into four parties as follows [3,11–16]:

- Top management (i.e., Chief Executive Officer (CEO) and Company Manager (CM)),
- Safety personnel (i.e., the safety managers and safety coordinators),
- Frontline supervisors (i.e., forepersons and superintendents), and
- Workers (i.e., carpenters and pipefitters).

Coordination and commitment of all levels of the construction workforce are vital to the success of any safety program and essential to facing any safety execution challenges in the construction industry [17]. Top management can enhance their safety programs by focusing on engineering improvements to equipment, methods, and materials and changing human behavior positively through education and training. It is the management's responsibility to ensure the success of the organization's safety plans, as its commitment to safety is a primary factor in that process [18,19]. Additionally, frontline supervisors play a vital role in the construction project's success as they are responsible for monitoring and reporting the various field activities. They also ensure the implementation of the organization's programs and are aware of the workplace's safety situation [5]. Furthermore, when available, coordinators/managers play a significant role in maintaining a safe work environment as they are responsible for preventing all types of construction accidents [20]. They are also required to ensure that the safety plans are followed and maintain a commitment to occupational health and safety standards and rules. Moreover, the workers themselves have a huge responsibility when it comes to reporting any situation that may cause danger to their lives, the way they work, or the amount of their accomplishment of the work assigned to them. At all times, they must follow the safety plans of their organization to ensure a safe workplace environment.

This paper will focus on evaluating the impact of safety measures compliance on reducing accidents in construction using the safety record of the Jordanian construction industry as a case study. Furthermore, it will examine the commitment of the Jordanian construction workforce to the requirements of a safe workplace and will investigate the top safety measures that lead to no major or frequent accident occurrence in the construction industry. In this research effort, Bayesian networks (BNs) as data mining techniques are used to develop different models and evaluate their ability to correctly classify no major or frequent accident occurrences in the construction industry. BNs have been adapted in this research effort since it provides a natural way to handle missing data, allows the combination of data with domain knowledge, facilitates learning about causal relationships between variables, offers a graphical presentation of the variables' relationships, and provides a method for avoiding the overfitting of data. They can provide good prediction accuracy even with rather small sample sizes. They are able to calculate the probability directly. They can be considered an alternative and/or an extension of logic for rational reasoning with incomplete and/or uncertain information. They have an inference engine to automate probabilistic reasoning and incorporate direct and indirect evidence into a single analysis to produce results for all needed comparisons within a connected network [21,22].

The BN is a directed acyclic graph (DAG) over a set of variables (U) and a set of probability tables (Bp). The BN represents joint probability distributions which are identified based on the following formulas:

$$P(U) = Qxi \in U\ p(Xi/pa(Xi)) \quad (1)$$

$$U = (X1; X2; \ldots; Xn) \quad (2)$$

$$Bp = p(Xi/pa(Xi)) \quad (3)$$

where $n \geq 1$ be a set of variables, $xi \in U$, pa(Xi) is the set of parents of Xi in BN, P(U) is the probability of U, and i = (1; 2; 3; . . . ; n). In BN, the vertices (nodes) denote the variables, and the edges (arcs) denote the relationships between the variables (interactions) (Mujalli 2019). A BN can classify the probability distribution of the variables without the arcs being causal, as the arcs between variables in a non-causal BN can demonstrate a sort of interrelationship(s) among these variables. In the classification development, y = x0 is the classifying variable, given a variable U as the set of attribute variables. A classifier, $h{:}U \rightarrow y$, is a function that classifies an instance of U to a value of y. A data set, D, that samples over (U, y) is used to learn a classifier in which the learning charge consists of discovering an appropriate BN given a data set D over U [23].

This paper is organized as follows. Section 2 includes construction industry safety literature. Section 3 introduces the methodology used throughout this paper. The measures that predict safety performance in the construction industry are identified in Section 4. Section 5 describes the survey data collection and analysis of the safety measures from survey results, defines the coding of the safety measures variables, and provides an analysis of safety measures compliance in the Jordanian construction industry. Section 6 illustrates the data oversampling, discusses the modeling and evaluation of the BN safety measures data, and presents the inference results. Section 7 presents the concluding remarks and recommendations.

2. Related Construction Industry Safety Literature

Alkilani reviewed the safety procedures, policies, and measures in an attempt to identify the constraints and challenges of implementing safety procedures in the Jordanian construction industry [24]. Alkilani collected the data using semi-structured interviews and analyzed them using the relative importance index. The research found that there was a lack of site monitoring, safety awareness, and safety knowledge for the majority of the contractors. He also reported a lack of data on safety accidents, injuries, and fatalities. In addition, Alkilani's study mentioned that small and medium enterprise contractors mainly focused on business growth while underestimating the value of safety procedures on the performance of construction workers. Finally, they revealed that the constraints to implementing good safety practices are regulations and policies, management commitment and involvement, and worker awareness.

Alubaid studied the factors affecting the safety policy of construction companies in Jordan [7]. This research used a survey to collect and analyze the data using means, standard deviations, relative importance indices, and correlation coefficients. The researcher found that 43% of the construction firms in Jordan had no standards or fixed policies for safety implementation. In addition, the safety policy of 66% of the construction companies working in Jordan was below international requirements. Alubaid reported that the largest construction companies considered safety equipment and personal protective equipment (PPE) as the top factors affecting safety, while rewards and penalties were the lowest ones.

Hiyassat concluded that despite the considerable amount of safety laws and legislation, in terms of quality and quantity, the enforcement of such laws was relatively weak in Jordan [25]. Hiyassat collected the data using a survey and interviews and used descriptive analysis to evaluate the data. The study indicated that the workers' commitment to the basic safety instructions was not strong. Additionally, the study stated that site visits by the safety inspectors of the Occupational Safety and Health (OSH) were very rare because of the small number of employed safety inspectors compared with the wide range of establishments in the different types of Jordanian industries. Furthermore, the study showed that many contractors were unaware of safety laws and instructions and that there was no safety orientation for new workers. The study recommended establishing a safety department within each of the contractors' organizations that are responsible for safety measures, inspections, and project safety visits.

El-Mashaleh examined the factors that affect safety management in the Jordanian construction industry [26]. He collected the data through an interview questionnaire and analyzed it using the weighted average. The study results showed that the factors that caused poor safety management included a lack of organizational safety policy, lack of basic safety training to recognize and avoid work risks, absence of safety meetings on a frequent basis, and rarely conducting safety inspections, which were crucial for enforcing safety at the construction site, lack of safety protective tools and PPEs, unavailability of safety signs and posters, and poor enforcement of the regulations.

Assbeihat discussed the obstacles that affect applying safety requirements in the Jordanian construction industry [27]. This study collected the data sets using interviews, observations, and investigations by a questionnaire and analyzed them using the weighted average and relative importance index methods. The results listed obstacles as the subcontractors' competence, non-Jordanian workers from different cultures, and the requirement of complex and tight-scheduled projects. The study indicated that despite the high unemployment rate in Jordan, there were many expatriate workers on construction sites. However, most of these workers did not hold work permits and were not registered. In addition, these workers did not have any knowledge about safety procedures. The contractors hired them on a short-term basis to avoid paying social security fees.

In addition, Assbeihat concluded that immoral bid-shopping practices could be harmful because they create an unsafe business environment promoting lower safety performance standards. The study recommended forcing general contractors to be responsible for all the safety requirements, tools, and regulations. Furthermore, Assbeihat suggested that penalties and incentives should be clearly stated in all construction contracts and subcontracts.

Al-Smadi studied the causes and rate of safety accidents in the construction industry in Jordan. He used questionnaires to collect data, and descriptive statistics were then used for demographic data [28]. One-way ANOVA was used to analyze the proposed hypothesis. The author concluded that the construction industry in Jordan had poor budget planning, a lack of safety awareness, and a lack of efficient materials management and resource allocation. As a result of these insufficient safety practices, the Jordanian construction industry has suffered financial and human casualties. The study categorized the factors that affect the safety accident rate according to demographic information, including gender, age, education background, position, experience, and company background. The study results showed that the younger, unmarried, male, and low-income workers had a higher probability of being in a safety accident. The research concluded that construction companies should increase awareness of safety practices and provide construction sites with a rapid response team to address safety incidents.

Al-Aubaidy assessed factors affecting underreporting of incidents in the United States construction industry [29]. The data was collected through a survey questionnaire and then analyzed using RIDIT, a statistical method used to analyze ordered qualitative data. Al-Aubaidy concluded that the incidence of these factors was more frequent in projects where the project safety team was doubtful about the accuracy of reporting. Al-Aubaidy's study results emphasized the urgent need to address underreporting factors in companies' efforts to obtain more accurate safety reporting.

Lee studied the properties of Korean construction projects, such as occupational safety and health management funds, safety management expenses, and others [30]. In addition, the author studied the accident prevention costs (APCs) to respond to high-accident rates in the Korean construction industry. He conducted a quantitative analysis of APC based on the surveyed projects. Descriptive statistics were used for demographic data, and one-way ANOVA was used to analyze the proposed hypothesis. The author concluded that the average ratio of the APC to the total targeted project cost was 1.95%. In addition, an average difference exists between groups according to owner types and construction types in the target project.

Bamfo examined the factors influencing construction labor productivity in Ghana. Bamfo's study assumes that productivity cannot be achieved without the influence of understanding the attitude of beneficiaries to work components on labor productivity in Ghana [31]. Bamfo collected the data using a survey and a statistical analysis; measures of association were then used to analyze the data. The author concluded that the critical factors were the age of beneficiaries, knowledge of beneficiaries, compliance with safety regulations, and the motivation of beneficiaries.

Awwad studied the existence and extent of the application of safety practices by Lebanese contractors, management commitment to safety, and opportunities for enhancing safe practices [17]. Awwad collected the data through an interview questionnaire with Lebanese contractors and analyzed it using descriptive analyses. Awwad's study showed a lack of awareness among small and medium size contractors about the necessity of developing and applying safety training programs on the job site. In contrast, large contractors showed a much stronger commitment to safety by using planned safety management programs and regular inspections.

Azmat explored the contributors to the safety hazards in the Saudi Arabian construction industry [32]. Azmat collected the data using a survey and used descriptive analysis to evaluate the data. ANOVA and correlation testing were also conducted on the collected data. The study results concluded that the management of construction organizations needed to improve its regulations and policies significantly.

However, none of the previous research efforts have considered the construction workforce and their associated safety measures. Additionally, there is no research effort that has analyzed the top safety measures that lead to no major or frequent accident occurrence, and no effort has focused on investigating the probability of no major or frequent accident occurrence in the Jordanian construction industry. Additionally, the previous research efforts have mainly analyzed the data based on descriptive statistics. To this end, the current research work is conducted to fill the gap in previous research efforts by using the BN classification models.

3. Methodology

This paper aims to evaluate the compliance of the company workforce to the safety regulations and requirements for the successful fulfillment of a safe workplace, to investigate the top safety measures that lead to no major or frequent accident occurrence in the Jordanian construction industry, and to determine the likelihood of having construction sites that are free of major or frequent accident occurrence. The proposed methodology is shown in Figure 1, and it is briefly described as follows:

Step 1: A comprehensive literature review was conducted to identify all relevant workforce safety measures associated with the company profile, top management, safety coordinator/manager, frontline supervisors, and workers. Interviews with the safety experts were conducted to solicit feedback to evaluate the identified subsets of variables for completion and accuracy. The outcome of this step was a final five subsets of safety measures that were validated by experts.

Step 2: A survey instrument was developed to collect the data from a representative set of Jordanian construction establishments to investigate the commitment to the identified safety measures and to explore the occurrence of major and frequent accidents in these establishments.

Step 3: The identified subsets were balanced using the Synthetic Minority Oversampling Technique (SMOTE). SMOTE synthesizes a new minority instance by looping them through the existing real minority instance to create a balanced class distribution [23]. At each loop iteration, neighbors from the closest neighbor K are randomly selected based on the required amount of oversampling. Then a new minority instance is synthesized somewhere between the minority instance and the selected neighbor. The new examples represent a combination between the features of the target case and the features of its neighbors. Typically, SMOTE is generalized to handle continuous variables. As an extension to SMOTE, SMOTE-NC was designed to deal with mixed datasets of nominal and continuous features. For the nearest neighbor computation, SMOTE-NC determines the distance between the real minority class sample and the identified k nearest neighbors using the continuous feature space. For every differing nominal feature, the algorithm considers the median of standard deviations for all continuous features for the minority class. The new set of synthetic samples is formed out of the real minority class without any duplicates or replacements. This effectively ensures the overall accuracy and ability to generalize and protect the data from overfitting. Many researchers have utilized this method and obtained improved correct classifications [23].

Step 4: Different BNs models were developed to evaluate their ability to classify no major or frequent accident occurrences correctly. The balanced subsets were then used to develop BNs using a combination of different search algorithms. These algorithms included Hillclimber, k2, Bayesian Dirichlet equivalent uniform (BDeu), minimum description length (MDL), and Akaike Information Criterion (AIC) since they are broadly used, are fairly quick, and produce an outstanding result in terms of overall network performance [23].

Step 5: The developed BNs were compared using a 10-fold cross-validation method based on their performance as obtained using performance measures including accuracy, true positive rate (TPR), true negative rate (TNR), F-measure (F1-Score), and the area under the curve (AUC). In addition, the corrected paired t-test was used to test their statistical significance. The outcome of this step was the best model for each subset.

Step 6: The significant safety measures were then extracted from each BN for each subset. The inference was performed to determine the probability of "do not have a major" or "no frequent" accident occurrence.

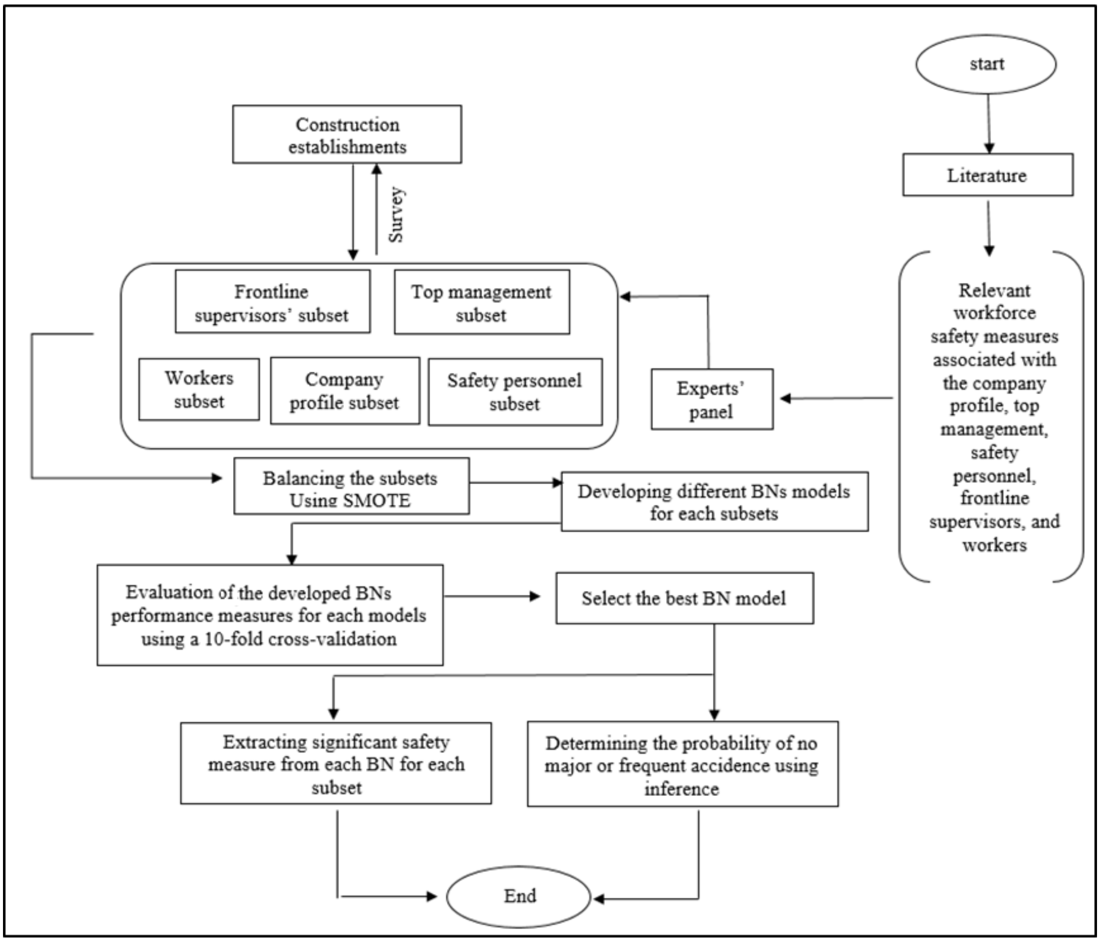

Figure 1. Study methodology.

4. Workforce Safety Measures in the Construction Industry

Identifying the measures that are predictive of safety performance is crucial to evaluating workforce safety performance. To effectively perform this task, effective safety values, practices, and responsibilities were identified in several studies [3,5,11,12,15,20,26,33–35]. For instance, Abudayyeh concluded that weekly working hours, safety budget, and dedication to safety regulations are essential indicators for an effective safety system [3]. They also indicated that construction companies with safety programs based on standard OSHA regulations had fewer injuries and illnesses than those who did not. In addition, weekly working hours at a certain limit are considered a safety risk, where employees who work more than 50 h a week have more injuries and illnesses than those who work fewer than 50 h. Additionally, companies that specified a budget for safety and allowed the safety coordinator/manager to spend more than $1000 experienced fewer injuries and illnesses than those that did not assign a specific safety. El-Mashaleh also stated that construction companies with full-time first-aid trained personnel among their staff experienced fewer injuries and illnesses than those without [26]. Al Bayati, in his study on the safety of the United States' construction, identifies two groups of safety variables [15]. The first group is the variables that are indicative of the underlying beliefs and principles that guide safety decisions making, which are introduced as the safety culture. The second group is the variables that are indicative of "the manifestation of these beliefs, principles, and policies in the form of practices and behaviors at the workplace," which is presented as a safety climate. Al Bayati's study resulted in comprehensive indicators of safety performance. In addition, the responsibilities of implementing these indicators among the stakeholders were categorized.

Accordingly, in the current study, the workforce safety measures for each of the five subsets have been created as a comprehensive set of indicators that capture the unique characteristics of the construction industry (see Table 1). Additionally, from the table, the responsibilities classification provides a clear, easy-to-understand, and easy-to-measure model for construction safety.

Table 1. Variables of the five subsets of the workforce safety measure and their categories with codifications.

Subset	Variable	Variable Code	Categories	Categories Codes	Count	Percentage
Part 1: Company profile	Type of sector for the establishment work	X1	Civil and Heavy Street or Road Construction	1	6	10.7
			Construction of Buildings	2	28	50.0
			Residential—Apartment Complex	3	7	12.5
			Residential—Single-family	4	5	8.9
			Special Trades Contract	5	10	17.9
				Total	56	100.0
	Role of the establishment work	X2	General Contractor	1	48	85.7
			Sub-Contractor	2	8	14.3
				Total	56	100.0
	The yearly estimated revenue of the establishment	X3	Less than $100 K	1	8	14.3
			$100 K– $500 K	2	11	19.6
			$500 K– $1 million	3	6	10.7
			More than $1 million, but less than $10 million	4	14	25.0
			More than $10 million	5	17	30.4
				Total	56	100.0
	Number of the daily workers working at the establishment	X7	Less than 10	1	9	16.1
			10–50	2	11	19.6
			50–100	3	7	12.5
			100–250	4	8	14.3
			More than 250	5	21	37.5
				Total	56	100.0

Table 1. *Cont.*

Subset	Variable	Variable Code	Categories	Categories Codes	Count	Percentage
	Number of employees working at the establishment	X8	Less than 10 10–50 50–100 100–250 More than 250	1 2 3 4 5 Total	5 8 10 10 23 56	8.9 14.3 17.9 17.9 41.1 100.0
	The establishment has a full-time safety coordinator/manager	X9	No Yes	0 1 Total	16 40 56	28.6 71.4 100.0
Part 2: Top management	The top management has strong core safety values that they abide by all	X10	No Yes	0 1 Total	4 52 56	7.1 92.9 100.0
	The top management responds to all incidents in a positive, learning way.	X11	No Yes	0 1 Total	8 48 56	14.3 85.7 100.0
	The top management allocates time and funds when corrective safety actions are required.	X12	No Yes	0 1 Total	4 52 56	7.1 92.9 100.0
	The top management adheres to safety requirements and procedures	X13	No Yes	0 1 Total	6 50 56	10.7 89.3 100.0
	The top management considers safety an integral part of the job, which receives the same amount of attention as other aspects	X14	No Yes	0 1 Total	9 47 56	16.1 83.9 100.0
	The top management has a formal safety training program for all new employees	X15	No Yes	0 1 Total	20 36 56	35.7 64.3 100.0
	The top management has periodic refresher training for each worker	X16	No Yes	0 1 Total	24 32 56	42.9 57.1 100.0
	The top management has a formal supervisory safety training program for all frontline supervisors	X17	No Yes	0 1 Total	21 35 56	37.5 62.5 100.0
	The top management has a program of regular site visits by safety coordinator/manager to review and control job hazards	X18	No Yes	0 1 Total	14 42 56	25.0 75.0 100.0
	The top management provides adequate personal protective equipment, first-aid equipment, and trained emergency personnel	X19	No Yes	0 1 Total	9 47 56	16.1 83.9 100.0
	The top management establishes a procedure for the emergency evacuation of injured workers	X20	No Yes	0 1 Total	13 43 56	23.2 76.8 100.0
	The top management has provisions for maintaining safety records and reporting accidents in compliance with safety regulations requirements	X21	No Yes	0 1 Total	18 38 56	32.1 67.9 100.0
Part 3: Safety coordinator/manager	The safety coordinator/manager tries to implement accident prevention techniques.	X22	No Yes NA	0 1 3 Total	3 43 10 56	5.4 76.8 17.9 100.0
	The safety coordinator/manager clearly communicates safety regulations and expectations	X23	No Yes NA	0 1 3 Total	4 43 9 56	7.1 76.8 16.1 100.0
	The safety coordinator/manager is approachable and receptive	X24	No Yes NA	0 1 3 Total	3 47 6 56	5.4 83.9 10.7 100.0

Table 1. *Cont.*

Subset	Variable	Variable Code	Categories	Categories Codes	Count	Percentage
	The safety coordinator/manager strives to improve overall site safety	X25	No	0	4	7.1
			Yes	1	46	82.1
			NA	3	6	10.7
				Total	56	100.0
	The safety coordinator/manager communicates accidents reports to workers in order to prevent future similar accidents	X26	No	0	6	10.7
			Yes	1	42	75.0
			NA	3	8	14.3
				Total	56	100.0
Part 4: Frontline supervisors	Frontline supervisors encourage the recording and reporting of all near misses	X27	No	0	8	14.3
			Yes	1	48	85.7
				Total	56	100.0
	Frontline supervisors are part of safety procedures reviewing	X28	No	0	12	21.4
			Yes	1	44	78.6
				Total	56	100.0
	Frontline supervisors correct unsafe conditions quickly	X29	No	0	4	7.1
			Yes	1	52	92.9
				Total	56	100.0
	Frontline supervisors lead by example when it comes to safety	X30	No	0	8	14.3
			Yes	1	48	85.7
				Total	56	100.0
	Frontline supervisors always ensure that workers are following proper safety regulations	X31	No	0	10	17.9
			Yes	1	46	82.1
				Total	56	100.0
Part 5: Workers	Workers feel okay with reporting unsafe conditions	X32	No	0	17	30.4
			Yes	1	39	69.6
				Total	56	100.0
	Workers know how/where to file an incident report	X33	No	0	17	30.4
			Yes	1	39	69.6
				Total	56	100.0
	Workers follow all safety policies and procedures	X34	No	0	17	30.4
			Yes	1	39	69.6
				Total	56	100.0
	Workers' actions suggest that safety training is received well	X35	No	0	18	32.1
			Yes	1	38	67.9
				Total	56	100.0
	Workers are part of safety procedures reviewing	X36	No	0	17	30.4
			Yes	1	39	69.6
				Total	56	100.0
	Workers feel confident that safety issues will be corrected if they reported them.	X37	No	0	12	21.4
			Yes	1	44	78.6
				Total	56	100.0
Y	No major/frequent accidents occurred in the establishment during the last 5 years (no safety penalties during the last 5 years) (Y)	Y	No	0	6	10.7
			Yes	1	41	73.2
			NA	3	9	16.1
				Total	56	100.0

5. Survey Data Collection and Analysis

To achieve the study objectives, a survey instrument was developed to collect relevant safety measures data in the Jordanian construction industry. The sequence of the questions was carefully ordered logically and formulated in six parts covering the five identified subsets of safety measures variables as well as major or frequent accident occurrence variables. All the variables were validated through interviews with safety experts to solicit feedback on variable completion and accuracy. Part 1 of the survey comprises the company profile (demographical information), which includes the type of work (sector) carried out by the establishment, the role of the establishment, and other related company information questions. Parts 2, 3, 4, and 5 contain questions about the safety measures of the top management, safety coordinator/manager, frontline supervisors, and workers, respectively. The sixth part includes questions regarding whether there was a major or frequent accident occurrence in the establishment in the last five years and whether there were safety penalties during the last five years. The survey was distributed by electronic mail to 100 construction establishment units specialized in multiple disciplines of civil engineering. A total of 56 units were considered valid responses. Table 1 summarizes the survey questions and the responses received from the valid participants.

5.1. Analysis of the Safety Measures from Survey Results

Of the responses received, 62.5% of respondents are top management representatives, 25% are frontline supervisors, and 12.5% are safety coordinators/managers. Most participants (66.1%) have over 10 years of experience, 19.6% have around 6–10 years, and about 14.3% have an experience of fewer than 5 years.

5.1.1. Part 1—Data: Demographics

According to Table 1, part 1, the difference between establishments' roles was crystal clear as 85.7% of firms that participated were general contractors, while 14.3% were subcontractor firms. This difference was also shown in sector diversity as the buildings specialized construction companies have a share of 50%, while special trade contract companies have a 17.9% share. The residential apartment complex and civil and heavy street or road construction have a share of 12.5% and 10.7%, respectively. Around 12.1% of the survey sample was special trades contractors, and 8.9% was for the residential single-family sector.

The survey also indicated that 37.5% of the responding companies had more than 250 daily workers, 19.6% with10 to 50 daily workers, followed by 16.1%, 14.3%, and 12.5% of the companies having less than 10, 100 to 250, and 50 to 100 daily workers, respectively. Around 71.4 % of the participating companies had a full-time safety coordinator/manager. Regarding the yearly estimated revenue of the participating companies, approximately 30.4% had more than $10 million, followed by 25% with revenues between $10 million and $1 million. Additionally, 19.6%, 14.3, and 10.7% of the companies had $100 K–$500 K, less than $100 K, and $500 K–$1 million in revenues, respectively. Around 41.1% of the participating companies had more than 250 permanent employees working, 17.9% had 100–250 employees, and only 8.9% had less than 10 employees.

5.1.2. Part 2—Data: Top Management

Table 1 summarizes the survey data from part 2; 92.9% of the top management had strong core safety values that they complied with. The same percentage was found for those companies that allocated time and funds when corrective safety actions were required. Around 85.7% of the top management responded to all incidents in a positive and learning way. Approximately 89.3% of top management adhered to the safety requirements and procedures, 83.9% considered safety as an integral part of the job, 64.3% had a formal safety training program for all new employees, 57.1% had periodic refresher training for each worker, and 37.5% did not have a formal supervisory safety training program for all frontline supervisors; additionally 75% of top management had a program for regular site visits by safety coordinator/manager to review and control job hazards, 83.9% provided adequate personal protective equipment, first-aid equipment, and trained emergency personnel, 23.2% did not establish a procedure for the emergency evacuation of injured workers, 32.1% had no provisions for maintaining safety records and reporting accidents in compliance with safety regulations requirements.

5.1.3. Part 3—Data: Safety Coordinator/Manager

Table 1 also shows the survey results from part 3; 77.8% of establishments have a safety coordinator/manager, while 22.2% do not. Around 67.8% of participating companies mentioned that their safety coordinators/managers tried to implement accident prevention techniques. In comparison, 17.9% said this did not apply to them as they did not have a safety coordinator in their firm. In total, 67.8% of safety coordinators/managers communicate safety regulations and expectations. Around 83.9% of safety coordinators/managers are approachable and receptive, and 82.1% strive to improve overall site safety. Only 10.7% of safety coordinators/managers do not communicate accident reports to workers to prevent future similar accidents.

5.1.4. Part 4—Data: Frontline Supervisors

It is evident that, from Table 1, part 4, approximately 85.7% of participants indicated that frontline supervisors encourage the recording and reporting of all near misses. It is worth noting here that safety policies are not considered practicable if they do not align well with operational safety. So, from the survey part 4, 78.6% of participants considered their companies' frontline supervisors to be part of the safety procedures reviewing team. In comparison, 21.4% of participants did not see their companies' frontline supervisors as part of this exercise. In addition, around 85.7% of the participants illustrated that frontline supervisors led by example regarding safety, while 14.3% did not seem to think the same about their company's frontline supervisors. Moreover, 92.9% of the survey participants stated that frontline supervisors corrected unsafe conditions immediately, while 7.1% did not think this was the case for their companies. Additionally, 82.1% of participants mentioned that frontline supervisors provided continuous supervision in their company to ensure the implementation of regulations by the workers.

5.1.5. Part 5—Data: Workers

Table 1 also shows the survey results according to survey part 5, construction workers. In this part, 30.4% of the survey respondents mentioned that workers were comfortable reporting unsafe conditions, and 30.4% indicated that workers did not know how/where to file an incident report. The survey results showed that around 30.4% of respondents felt that workers did not follow the safety regulations in their establishments. In addition, the results showed that 32.1% of respondents believed that workers' actions suggested that safety training was well received. The results also indicated that 75.6% of the respondents did not believe that workers were part of reviewing safety procedures. However, 78.6% felt confident that safety issues would be corrected if workers reported them.

5.2. Defining and Coding Safety Measures Variables

Table 1 illustrates the safety measures (variables) from each workforce subset and their codifications (Variable code). The company profile subset includes X1, X2, X3, X7, and X8 variable codes, the top management subset includes X9, X10, X11, X12, X13, X14, X15, X16, X17, X18, X19, X20, and X21 variable codes, the safety coordinator/manager subset includes X22, X23, X24, X25, and X26 variable codes, the frontline supervisor subset includes X27, X28, X29, X30, and X31, and the worker subset includes X32, X33, X34, X35, X36, X37. No "major/frequent accidents occurred in the establishment during the last five years (no safety penalties during the last five years) (Y)" is used as a binary response variable, while the other independent variables are nominal.

5.3. Analysis of Safety Measures Compliance in the Jordanian Construction Industry

Cross-tabulation was used to analyze the responses of the respondents to the five subsets of workforce safety measures. Table 2 illustrates the contribution of safety measures compliance of each subset to no major/frequent accidents.

Table 2. Cross tabulations for variables based on accident occurrence.

Model	Independent Variables	Categories	No accidents Occurrence in the Establishment during the Last Five Years (Y)							
			0		1		NA		Total	
			Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage
Model 0	X1	1	0	0.0	4	7.1	2	3.6	6.0	10.7
		2	3	5.4	21	37.5	4	7.1	28.0	50.0
		3	2	3.6	4	7.1	1	1.8	7.0	12.5
		4	0	0.0	4	7.1	1	1.8	5.0	8.9
		5	1	1.8	8	14.3	1	1.8	10.0	17.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X2	1	5	8.9	34	60.7	9	16.1	48.0	85.7
		2	1	1.8	7	12.5	0	0.0	8.0	14.3
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X3	1	1	1.8	5	8.9	2	3.6	8.0	14.3
		2	2	3.6	7	12.5	2	3.6	11.0	19.6
		3	0	0.0	6	10.7	0	0.0	6.0	10.7
		4	0	0.0	13	23.2	1	1.8	14.0	25.0
		5	3	5.4	10	17.9	4	7.1	17.0	30.4
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X7	1	1	1.8	4	7.1	4	7.1	9.0	16.1
		2	1	1.8	8	14.3	2	3.6	11.0	19.6
		3	1	1.8	5	8.9	1	1.8	7.0	12.5
		4	0	0.0	8	14.3	0	0.0	8.0	14.3
		5	3	5.4	16	28.6	2	3.6	21.0	37.5
		Total	6	10.7	41	73.2	9	16.1	56.0	100
	X8	1	2	3.6	3	5.4	0	0.0	5.0	8.9
		2	0	0.0	4	7.1	4	7.1	8.0	14.3
		3	1	1.8	6	10.7	3	5.4	10.0	17.9
		4	0	0.0	10	17.9	0	0.0	10.0	17.9
		5	3	5.4	18	32.1	2	3.6	23.0	41.1
		Total	6	10.7	41	73.2	9	16.1	56.0	100
	X9	0	2	3.6	10	17.9	4	7.1	16.0	28.6
		1	4	7.1	31	55.4	5	8.9	40.0	71.4
		Total	6	10.7	41	73.2	9	16.1	56.0	100
Model 1	X10	0	0	0.0	4	7.1	0	0.0	4.0	7.1
		1	6	10.7	37	66.1	9	16.1	52.0	92.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X11	0	0	0.0	6	10.7	2	3.6	8.0	14.3
		1	6	10.7	35	62.5	7	12.5	48.0	85.7
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X12	0	0	0.0	4	7.1	0	0.0	4.0	7.1
		1	6	10.7	37	66.1	9	16.1	52.0	92.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X13	0	0	0.0	6	10.7	0	0.0	6.0	10.7
		1	6	10.7	35	62.5	9	16.1	50.0	89.3
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X14	0	1	1.8	7	12.5	1	1.8	9.0	16.1
		1	5	8.9	34	60.7	8	14.3	47.0	83.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X15	0	1	1.8	13	23.2	6	10.7	20.0	35.7
		1	5	8.9	28	50.0	3	5.4	36.0	64.3
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X16	0	0	0.0	18	32.1	6	10.7	24.0	42.9
		1	6	10.7	23	41.1	3	5.4	32.0	57.1
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X17	0	0	0.0	17	30.4	4	7.1	21.0	37.5
		1	6	10.7	24	42.9	5	8.9	35.0	62.5
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X18	0	1	1.8	10	17.9	3	5.4	14.0	25.0
		1	5	8.9	31	55.4	6	10.7	42.0	75.0
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0

Table 2. *Cont.*

Model	Independent Variables	Categories	No accidents Occurrence in the Establishment during the Last Five Years (Y)							
			0		1		NA		Total	
			Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage
	X19	0	0	0.0	8	14.3	1	1.8	9.0	16.1
		1	6	10.7	33	58.9	8	14.3	47.0	83.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X20	0	1	1.8	11	19.6	1	1.8	13.0	23.2
		1	5	8.9	30	53.6	8	14.3	43.0	76.8
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X21	0	1	1.8	15	26.8	2	3.6	18.0	32.1
		1	5	8.9	26	46.4	7	12.5	38.0	67.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
Model 2	X22	0	0	0.0	3	5.4	0	0.0	3.0	5.4
		1	6	10.7	31	55.4	6	10.7	43.0	76.8
		3	0	0.0	7	12.5	3	5.4	10.0	17.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X23	0	1	1.8	3	5.4	0	0.0	4.0	7.1
		1	5	8.9	31	55.4	7	12.5	43.0	76.8
		3	0	0.0	7	12.5	2	3.6	9.0	16.1
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X24	0	0	0.0	3	5.4	0	0.0	3.0	5.4
		1	5	8.9	35	62.5	7	12.5	47.0	83.9
		3	1	1.8	3	5.4	2	3.6	6.0	10.7
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X25	0	1	1.8	3	5.4	0	0.0	4.0	7.1
		1	5	8.9	34	60.7	7	12.5	46.0	82.1
		3	0	0.0	4	7.1	2	3.6	6.0	10.7
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X26	0	0	0.0	4	7.1	2	3.6	6.0	10.7
		1	6	10.7	31	55.4	5	8.9	42.0	75.0
		3	0	0.0	6	10.7	2	3.6	8.0	14.3
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
Model 3	X27	0	0	0.0	7	12.5	1	1.8	8.0	14.3
		1	6	10.7	34	60.7	8	14.3	48.0	85.7
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X28	0	0	0.0	10	17.9	2	3.6	12.0	21.4
		1	6	10.7	31	55.4	7	12.5	44.0	78.6
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X29	0	0	0.0	4	7.1	0	0.0	4.0	7.1
		1	6	10.7	37	66.1	9	16.1	52.0	92.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X30	0	1	1.8	7	12.5	0	0.0	8.0	14.3
		1	5	8.9	34	60.7	9	16.1	48.0	85.7
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X31	0	0	0.0	8	14.3	2	3.6	10.0	17.9
		1	6	10.7	33	58.9	7	12.5	46.0	82.1
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
Model 4	X32	0	0	0.0	12	21.4	5	8.9	17.0	30.4
		1	6	10.7	29	51.8	4	7.1	39.0	69.6
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X33	0	1	1.8	12	21.4	4	7.1	17.0	30.4
		1	5	8.9	29	51.8	5	8.9	39.0	69.6
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0

Table 2. *Cont.*

Model	Independent Variables	Categories	No accidents Occurrence in the Establishment during the Last Five Years (Y)							
			0		1		NA		Total	
			Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage
	X34	0	1	1.8	13	23.2	3	5.4	17.0	30.4
		1	5	8.9	28	50.0	6	10.7	39.0	69.6
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X35	0	0	0.0	14	25.0	4	7.1	18.0	32.1
		1	6	10.7	27	48.2	5	8.9	38.0	67.9
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X36	0	1	1.8	14	25.0	2	3.6	17.0	30.4
		1	5	8.9	27	48.2	7	12.5	39.0	69.6
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0
	X37	0	0	0.0	10	17.9	2	3.6	12.0	21.4
		1	6	10.7	31	55.4	7	12.5	44.0	78.6
		Total	6	10.7	41	73.2	9	16.1	56.0	100.0

For the company profile subset variables, approximately 37.5% of the respondents with no major accident occurrences belonged to the construction of buildings, followed by special trade subcontractors (14.3%). The remaining sectors had approximately the same percentage of 7.1 each. Obviously, the general contractor was a much better establishment with no major or frequent accident occurrence (60.7% of respondents) than the subcontractor establishment (12.5% of respondents). In addition, the responses showed that establishments with yearly estimated revenue between $1 million and $10 million were mostly the ones with no major or frequent accident occurrences, with 23.2%. Interestingly, establishments with more than 250 daily workers and 250 permanent employees were also the ones with no major or frequent accident occurrences, with 28.6% and 32.1%, respectively. Clearly, the establishments with a full-time safety coordinator/manager had a higher percentage (55.4%) of no major or frequent accident occurrence when compared with those (17.9%) that did not have a full-time safety coordinator/manager.

According to the top management safety measure, it was found that top management with strong core safety values (66.1%) complied with had less chance of major accident occurrence. In addition, the results showed that top management who responded (62.5%) to all incidents in a positive, learning way had a high chance of no major or frequent accident occurrence. Additionally, those who allocated time and funds (66.1%) when corrective safety actions were required were the most expected not to have a major or frequent accident occurrence. The results also illustrated that 66.5% of no major or frequent accident occurrences are achieved if top management adheres to safety requirements and procedures. Achieving 60.7% of no major or frequent accident occurrences is also dependent on top management considering safety as an integral part of the job and giving it the same amount of attention as other aspects of the work. Additionally, no major or frequent accident occurrences are achieved when top management has a formal safety training program (50%), has periodic refresher training (41.1%) for each worker, has a formal safety training program for all frontline supervisors (42.9%), has a program of regular site visits by safety coordinator/manager to review and control job hazards (55.4%), provides adequate personal protective equipment, first-aid equipment, and trained emergency personnel (58.9%), establishes procedures for the emergency evacuation of injured workers (53.6%), and has provisions for maintaining safety records and reporting accidents in compliance with safety regulations requirements (46.4%).

The results from the safety coordinator/manager part showed that there was no major or frequent accident occurrence (55.4%) when safety coordinators/managers tried to implement accident prevention techniques, clearly communicated safety regulations and expectations, and communicated accidents reports to workers in order to prevent future similar accidents. Additionally, no major or frequent accident occurrences were also the result of safety coordinators/managers who were approachable and receptive (62.5%) and who strived to improve (60.7%).

According to the frontline supervisors' variables subsets, it was found that the frontline supervisors who quickly corrected unsafe conditions had the highest percentage of no major accident occurrence, which is 66.1%. In addition, no major or frequent accident occurrences resulted from frontline supervisors ensuring that workers followed proper safety regulations (58.9%) and were part of the safety procedures reviewing team (55.4%). It was also shown that 60.7% of no major or frequent accident occurrences resulted from frontline supervisors leading by example when it came to safety and encouraging the recording and reporting of all near misses.

Finally, for the workers' variables subset, it was found that workers felt confident that safety issues would be corrected if they reported them had the highest percentage (55.4%) of no major accidents. In addition, no major or frequent accident occurrences resulted from workers feeling okay to report unsafe conditions and knowing how/where to file an incident report (51.8). Furthermore, the results showed that following all safety policies and procedures by workers contributed to 50% of no major or frequent accident occurrences. Finally, the result showed no major or frequent accident occurrence (48.2%) when workers' actions suggested that safety training was received well and that workers were part of the safety procedures reviewing team.

6. Bayesian Network (BN) Modeling

6.1. Balancing Subsets by Oversampling

As shown in Table 1, the variable "no major/or frequent accident occurrence" has nine missing values as received from respondents. Due to the small sample size, the research team decided not to delete these records and to impute their values using the unsupervised variable filter to replace missing values. The filter replaces missing data with the mode of all known values of the safety measure variable in the class where the record is missing data [36]. In addition, due to the small sample size of the respondents, it was decided to use oversampling techniques to balance the variable response categories (Yes: no major/or frequent accident occurrence; No: a major/or frequent accident occurrence) since the response variable is highly imbalanced as shown in Table 3. Imbalanced datasets problems occur when there are many more cases of one class than the other, which may affect the ability of the classifier to classify new cases correctly. In the study herein, cases identified as having no major/or frequent accident occurrence (yes) represent approximately 89%, while those having major/or frequent accident occurrence (no) represent 11%, consequently resulting in classifying new cases as (yes) 89% of the time. Sampling is usually adapted to deal with the imbalanced datasets problem using one of two approaches: the Under-sampling method or Oversampling. While the Under-sampling approach removes cases from the class with more cases, the Oversampling approach adds more cases to the class with fewer cases. In this research effort, the workforce safety measures datasets were balanced prior to model development using the SMOTE.

Table 3. Distribution of the class variable categories in imbalanced and balanced datasets.

	Class variable Categories Count and Percentage		
Dataset	No	Yes	Total
Imbalanced	6 (11%)	50 (89%)	56
Balanced	48 (49%)	50 (51%)	98

6.2. Safety Measures BN Data Modeling and Evaluation

In order to model the five subsets of safety measures, five models were developed to find out which variables (safety measures) are associated with the no major or frequent accident occurrence in the construction industry in Jordan. Weka software was adapted in this study to develop the BNs. This software is implemented in Java language. The developed BNs models are based on datasets that have the same number of records but different numbers of variables in which the dataset that is used to develop model 0 has five variables, model 1 has thirteen variables, model 2 has six variables, model 3 has five variables, and model 4 has six variables as follows:

Model 0 is the company profile model and used five variables as follows:

X1 is the type of sector for the establishment work,

X2 is the role of the establishment work,

X3 is the yearly estimated revenue of the establishment,

X7 is the number of daily workers working at the establishment,

X8 is the number of employees working at the establishment.

Model 1 is the top management model and used thirteen variables as follows:

X9 is the establishment has a full-time safety coordinator/manager,

X10 is the top management has strong core safety values that they abide by all,

X11 is the top management responds to all incidents in a positive, learning way,

X12 is the top management allocates time and funds when corrective safety actions are required,

X13 is the top management adheres to safety requirements and procedures,

X14 is the top management considers safety an integral part of the job, which receives the same amount of attention as other aspects,

X15 is the top management has a formal safety training program for all new employees,

X16 is the top management has periodic refresher training for each worker,

X17 is the top management has a formal supervisory safety training program for all frontline supervisors,

X18 is the top management has a program of regular site visits by the safety coordinator/manager to review and control job hazards,

X19 is the top management provides adequate personal protective equipment, first-aid equipment, and trained emergency personnel,

X20 is the top management establishes a procedure for the emergency evacuation of injured workers,

X21 is the top management has provisions for maintaining safety records and reporting accidents in compliance with safety regulations requirements.

Model 2 is the safety coordinator/manager model and used five variables as follows:

X22 is the safety coordinator/manager tries to implement accident prevention techniques,

X23 is the safety coordinator/manager clearly communicates safety regulations and expectations,

X24 is the safety coordinator/manager is approachable and receptive,

X25 is the safety coordinator/manager strives to improve overall site safety,

X26 is the safety coordinator/manager communicates accident reports to workers to prevent future similar accidents.

Model 3 is the frontline supervisor model, using five variables as follows:

X27 is frontline supervisors encourage the recording and reporting of all near misses,

X28 is frontline supervisors are part of safety procedures reviewing,

X29 is frontline supervisors correct unsafe conditions quickly,

X30 is frontline supervisors lead by example when it comes to safety,

X31 is frontline supervisors always ensure workers follow proper safety regulations.

Model 4 is the worker model, which uses six variables as follows:

X32 is workers feel okay with reporting unsafe conditions,

X33 is workers know how/where to file an incident report,

X34 is workers follow all safety policies and procedures,

X35 is workers' actions suggest that safety training is received well,

X36 is workers are part of safety procedures reviewing,

X37 is workers feel confident that safety issues will be corrected if they report them.

As aforementioned, originally, the datasets had 56 records that were oversampled using SMOTE to balance the class variable labels. Consequently, the data that was used to develop each model consisted of 98 records. Using the search algorithms of Hillclimber and K2 along with the score metrics of Bdeu, MDL, and AIC, different BNs were developed for each model. Six BNs were developed for each model using different combinations of search and score metrics. In addition, 10-folds cross-validation was used, and the average of 10 runs for the test set was recorded. For example, for model 0, there were six BNs: the first BN was developed using a combination of Hillclimber search and Bdeu score, the second BN was developed using a combination of Hillclimber search and MDL score, the third BN was developed using a combination of Hillclimber search and AIC score, the fourth BN was developed using a combination of K2 search and Bdeu score, the fifth BN was developed using a combination of K2 search and MDL score, and the sixth BN was developed using a combination of K2 search and AIC score.

In machine learning, the quality of the dataset is discovered based on the classification performance of inductive learning algorithm(s) trained on the given dataset [37]. Therefore, four widely used performance metrics are considered in this paper to evaluate and compare the BNs classification and prediction performance of each model developed on the original and oversampled subsets to analyze "no major/or frequent accident occurrence." These include accuracy, true positive rate (TPR) (sensitivity), true negative rate (TNR) specificity, F-measure (F1-Score), and the area under the curve (AUC). The accuracy is the percentage of cases that the classifier successfully classified. Sensitivity is defined as the percentage of all observed positive cases that were accurately predicted. Specificity is the percentage of accurately predicted negative cases among all the observed negative cases. F-score is the harmonic mean of the model's precision and recall. The equations for the performance metrics used in this paper are as follows:

$$\text{Accuracy} = (TP + TN)/(TP + FP + TN + FN) \quad (4)$$

$$TPR = TP/(TP + FP) \quad (5)$$

$$TNR = TN/(TN + FP) \quad (6)$$

$$\text{F1-Score} = 2 * (\text{Precision} * \text{Recall})/(\text{Precision} + \text{Recall}) \quad (7)$$

$$\text{Recall} = TP/(TP + FN) \quad (8)$$

$$\text{Precision} = TP/(TP + FP) \quad (9)$$

where TN is the number of negative cases correctly classified for each class (True Negatives), FP is the number of negative cases incorrectly classified as positive (False Positives) for each class, FN is the number of positive cases incorrectly classified as negative (False Negatives) for each class, and TP is the number of positive cases correctly classified for each class (True Positives). AUC is the area below a curve with sensitivity plotted on the y-axis and 1-specificity [38].

Table 4 displays the average results of the five performance metrics for each of the six BNs used for the five different models developed. A corrected paired t-test was used to test their statistical significance.

As shown in Table 4, for model 0, the algorithm that obtained the best results in terms of TNR, F1 score, and AUC is Hillclimber+AIC. For model 1, the algorithm that achieved the best results in terms of accuracy, TNR, and F1 score is K2+AIC, whereas, for model 2, the algorithm that achieved the best results in terms of accuracy, TNR, F1 score, and AUC is K2+BDeu. For model 3, the algorithms that obtained the best results in terms of accuracy, TNR, F1 score, and AUC are K2+MDL and K2+AIC. Finally, for model 4, the algorithm that obtained the best results in terms of TNR and F1 score is K2+Bdeu.

Table 4. The performance evaluation of the BNs based on the test subset.

Safety Measure Subset Model	BN Model Algorithm	Performance Measure Average of 10 Runs (Standard Deviation)					Best Algorithm
		Accuracy	TPR	TNR	F1-Score	AUC	
Model 0	1. Hillclimber+Bdeu	0.872 (0.010)	0.915 (0.116)	0.830 (0.162)	0.877 (0.098)	0.907 (0.089)	3
	2. Hillclimber+MDL	0.847 (0.010)	0.915 (0.116)	0.782 (0.180)	0.857 (0.093)	0.860 (0.110)	
	3. Hillclimber+AIC	0.886 (0.092)	0.915 (0.116)	0.858 (0.154)	0.888 (0.090)	0.895 (0.104)	
	4. K2+Bdeu	0.863 (0.010)	0.915 (0.116)	0.812 (0.175)	0.869 (0.093)	0.909 (0.097)	
	5. K2+MDL	0.856 (0.011)	0.915 (0.116)	0.800 (0.191)	0.865 (0.099)	0.908 (0.099)	
	6. K2+AIC	0.879 (0.011)	0.915 (0.116)	0.844 (0.183)	0.884 (0.101)	0.893 (0.103)	
Best performance		6	0	3	3	3	
Model 1	1. Hillclimber+Bdeu	0.778 (0.011)	0.988 (0.051)	0.580 (0.214)	0.820 (0.082)	0.805 (0.116)	6
	2. Hillclimber+MDL	0.746 (0.011)	1.000 (0.000)	0.504 (0.214)	0.800 (0.073)	0.730 (0.143)	
	3. Hillclimber+AIC	0.782 (0.011)	0.992 (0.042)	0.582 (0.209)	0.822 (0.080)	0.783 (0.120)	
	4. K2+Bdeu	0.799 (0.011)	0.979 (0.065)	0.628 (0.215)	0.832 (0.082)	0.799 (0.109)	
	5. K2+MDL	0.790 (0.011)	0.979 (0.065)	0.610 (0.210)	0.825 (0.082)	0.781 (0.123)	
	6. K2+AIC	0.805 (0.010)	0.979 (0.065)	0.640 (0.199)	0.836 (0.077)	0.798 (0.108)	
Best performance		6	3	6	6	3	
Model 2	1. Hillclimber+Bdeu	0.624 (0.095)	1.000 (0.000)	0.264 (0.186)	0.726 (0.053)	0.622 (0.127)	4
	2. Hillclimber+MDL	0.600 (0.089)	1.000 (0.000)	0.216 (0.174)	0.712 (0.049)	0.611 (0.138)	
	3. Hillclimber+AIC	0.599 (0.088)	1.000 (0.000)	0.214 (0.174)	0.712 (0.049)	0.610 (0.137)	
	4. K2+Bdeu	0.653 (0.010)	1.000 (0.000)	0.320 (0.199)	0.742 (0.062)	0.658 (0.107)	
	5. K2+MDL	0.622 (0.094)	1.000 (0.000)	0.260 (0.183)	0.724 (0.054)	0.619 (0.099)	
	6. K2+AIC	0.623 (0.095)	1.000 (0.000)	0.262 (0.186)	0.725 (0.055)	0.619 (0.099)	
Best performance		4	0	4	4	4	
Model 3	1. Hillclimber+Bdeu	0.644 (0.011)	1.000 (0.000)	0.304 (0.206)	0.737 (0.063)	0.650 (0.128)	5, 6
	2. Hillclimber+MDL	0.606 (0.010)	1.000 (0.000)	0.230 (0.194)	0.717 (0.057)	0.611 (0.125)	
	3. Hillclimber+AIC	0.638 (0.099)	1.000 (0.000)	0.292 (0.194)	0.734 (0.059)	0.648 (0.125)	
	4. K2+Bdeu	0.662 (0.010)	1.000 (0.000)	0.340 (0.204)	0.748 (0.065)	0.660 (0.112)	
	5. K2+MDL	0.662 (0.010)	1.000 (0.000)	0.340 (0.204)	0.748 (0.065)	0.661 (0.112)	
	6. K2+AIC	0.662 (0.010)	1.000 (0.000)	0.340 (0.204)	0.748 (0.065)	0.661 (0.111)	
Best performance		4, 5, 6	0	4, 5, 6	4, 5, 6	5, 6	
Model 4	1. Hillclimber+Bdeu	0.755 (0.011)	0.979 (0.065)	0.540 (0.216)	0.801 (0.076)	0.764 (0.107)	4
	2. Hillclimber+MDL	0.709 (0.011)	0.985 (0.053)	0.444 (0.204)	0.773 (0.075)	0.714 (0.124)	
	3. Hillclimber+AIC	0.747 (0.011)	0.981 (0.061)	0.522 (0.209)	0.796 (0.080)	0.749 (0.123)	
	4. K2+Bdeu	0.756 (0.011)	0.979 (0.065)	0.542 (0.217)	0.802 (0.075)	0.755 (0.123)	
	5. K2+MDL	0.729 (0.011)	0.989 (0.046)	0.480 (0.205)	0.786 (0.074)	0.743 (0.126)	
	6. K2+AIC	0.752 (0.011)	0.979 (0.065)	0.534 (0.215)	0.799 (0.078)	0.750 (0.128)	
Best performance		3	5	4	4	1	

Each BN has its own DAG or tree. Using the DAG, the interrelationships of the variables can be obtained. That is, it can be found out which variables significantly affect the class variable, which are the variables that have an arc connected to the class variable. The BN trees for each selected algorithm in each model are shown in Figures 2 and 3. Figure 2 shows models 0 and 1, and Figure 3 shows models 2, 3, and 4. For example, in Figure 2, for model 0, it can be seen that the variables that have an arc connected to the class variable are X1 and X3. This means the two variables associated with the response variable are variables X1 and X3. In model 1, the variables that are associated with the response variable are X10, X11, X15, X16, X17, and X19. Figure 3 shows that variables X22 and X26 were associated with the response variable in model 2. In model 3, the two BN trees for K2+MDL and K2+AIC were the same, in which the variables X27 and X28 were associated with the response variable. Finally, in model 4, variables X32, X35, and X36 were associated with the response variable.

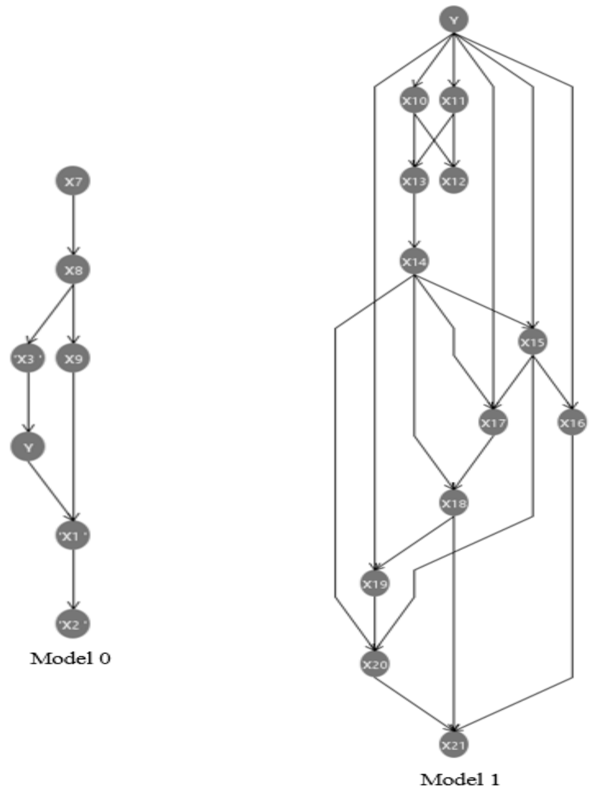

Figure 2. BN trees for models 0 and 1.

Inference in BNs refers to computing the conditional probability of some variables, given that other variables are set to evidence. Inference may be carried out for a specific value of a variable, given evidence on the value of another variable. Thus, to identify the most significant values (categories) of safety measures that affect the no occurrence of a major or frequent accident, the inference was performed. Each BN has its own conditional probability table. Using these conditional probability tables, the probability of no occurrence of a major or frequent accident was calculated, as shown in Table 5. For example, in Table 5, for model 0, if the class variable has evidence of (Yes), then the probabilities associated with this evidence for each category under each variable can be calculated. As shown, under X1, the probability of one is equal to 0.01312, two is equal to 0.4685, three is equal to 0.0999, four is equal to 0.1122, and five is equal to 0.1879. This means that when setting evidence for Y to be Yes, and looking at variable X1, we can see that the category that had the highest probability of occurrence is two.

6.3. Discussion of BN Model and Inference Results

The BNs were developed using a combination of search algorithms, including Hillclimber, and k2, with score metrics of BDeu, MDL, and AIC to determine the most significant variables contributing to the no major or frequent accident occurrence in each subset. For further analysis, the inference was performed in which evidence was set to a specific category of the variables that were directly associated with an arc with no major or frequent accident occurrence. The probability of no major or frequent accident occurrence was calculated, as shown in Table 4.

6.3.1. Demographics

According to the performance metric, it was found that the best algorithm for developing BN for the company profile variables subset was Hillclimber+AIC. The result of this subset modeling showed that the safety measures directly associated with no major or frequent accident occurrence were the type of sector for the establishment work and the yearly estimated revenue of the establishment. Inference in BN showed that the probability of 46.85% of the sector with no major accident occurrences was the construction of buildings, followed by special trade subcontractors with a probability equal to 18.79%. At the same time, the residential—apartment complex sector had a low probability (9.99%) of not having major accidents.

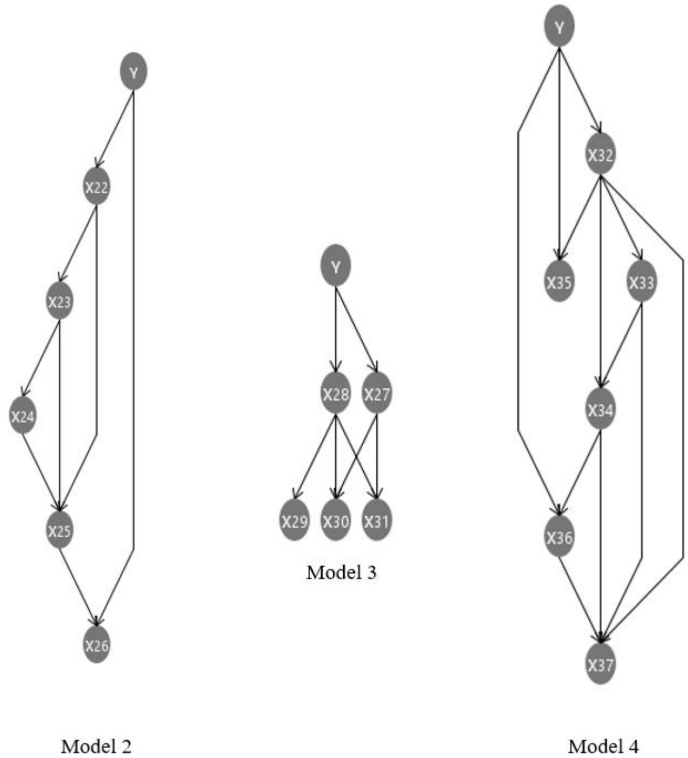

Figure 3. BN trees for models 2, 3, and 4.

For the yearly estimated revenue, the inference in BN showed that the establishments with yearly estimated revenue between $1 million and $10 million and those with yearly estimated revenue of more than $10 million had the highest probability of no major or frequent accident occurrence which were equal to 27.51% and 27.27%, respectively. These results are consistent with what Oh found in his study examining construction safety in Korea [39].

Also, the model results showed that the general contractor was a much better establishment role with a probability of having no major or frequent accident occurrence equal to 84.91% than the subcontractor establishment role with a probability equal to 15.08%. This is consistent with results Jazayeri found in the United States, where performance issues in subcontracting included the subcontractor selection process and safety concerns on construction job sites [40]. However, Assbeihat mentioned that there was an increasing need for subcontractors in the Jordanian construction industry, which might have led to unorganized selection, uncontrolled coordination, and unethical bid-shopping practices [27]. These issues and conditions stand as barriers to improving safety performance and may lead to increased injury and fatality rates in the Jordanian construction industry.

Clearly, from the inference in the model, the establishment with a full-time safety coordinator/manager had a higher probability (72.84%) of no major or frequent accident occurrence when compared with the establishments with full-time safety coordinators/managers (27.15). However, 28.6% of the establishments in Jordan do not have a full-time safety coordinator/manager.

Table 5. Inference results for categories of variables when setting evidence to the response variable (no occurrence of major or frequent accidents).

Setting Evidence to Y = Yes			
Model	**Independent Variables**	**Categories**	**Probability of Categories in Variables after Setting Evidence to the Response Variable**
Model 0	X1	1	0.1312
		2	**0.4685**
		3	0.0999
		4	0.1122
		5	0.1879
	X2	1	**0.8491**
		2	0.1508
	X3	1	0.145
		2	0.1789
		3	0.1281
		4	**0.2751**
		5	0.2727
	X7	1	0.1366
		2	0.1723
		3	0.1093
		4	0.1113
		5	**0.4703**
	X8	1	0.0995
		2	0.1356
		3	0.1591
		4	0.1411
		5	**0.4644**
	X9	0	0.2715
		1	**0.7284**
Model 1	X10	0	0.1078
		1	0.8921
	X11	0	0.1666
		1	**0.8333**
	X12	0	0.1
		1	**0.8999**
	X13	0	0.1284
		1	**0.8715**
	X14	0	0.152
		1	**0.8479**
	X15	0	0.376
		1	**0.6239**
	X16	0	0.4759
		1	**0.524**
	X17	0	0.408
		1	**0.5919**
	X18	0	0.2492
		1	**0.7507**
	X19	0	0.1868
		1	**0.8131**
	X20	0	0.2132
		1	**0.7867**
	X21	0	0.3459
		1	**0.654**
Model 2	X22	0	0.0679
		1	**0.7281**
		3	0.2038
	X23	0	0.0676
		1	**0.764**
		3	0.1682
	X24	0	0.0629
		1	**0.826**
		3	0.111
	X25	0	0.0878
		1	**0.7955**
		3	0.1166
	X26	0	0.1407
		1	**0.7015**
		3	0.1576
Model 3	X27	0	0.1666
		1	**0.8333**
	X28	0	0.245
		1	**0.7549**
	X29	0	0.079
		1	**0.9209**
	X30	0	0.1507
		1	**0.8492**
	X31	0	0.1921
		1	**0.8078**
Model 4	X32	0	0.3431
		1	**0.6568**
	X33	0	0.2714
		1	**0.7287**
	X34	0	0.2689
		1	**0.731**
	X35	0	0.3641
		1	**0.6358**
	X36	0	0.2968
		1	**0.7031**
	X37	0	0.2211
		1	**0.7788**

Furthermore, establishments with more than 250 daily workers and more than 250 permanent employees had the highest probability value (47.03%), each with regard to having no major or frequent accident occurrence. According to Tam, companies are classified into small (20 or fewer employees), medium (21 to 99 employees), and large (100 or more employees) [41]. Using this categorization, larger establishments generally have better safety records. These results are consistent with Alkilani's conclusions, where he mentions that the largest construction firms care the most about the factors affecting safety while the smallest ones are less [24].

6.3.2. Top Management

The K2+AIC algorithm was the best for the BN of the top management variables subset. From this model, it is concluded that the safety measure which is directly associated with no major or frequent accident occurrence is when top management (1) has strong core safety values that they abide by, (2) responds to all incidents in a positive, learning way, (3) has a formal safety training program for all new employees, (4) has periodic refresher training for each worker, (5) has a formal supervisory safety training program for all frontline supervisors, and (6) provides adequate personal protective equipment, first-aid equipment, and trained emergency personnel.

The inference in BN disclosure is that the probability of 89.21% of not having major accidents if the top management complies with strong core safety values. This result is logical since the compliance of the top management with strong core safety values is a critical component of safety. It refers to workers' perceptions of the degree to which their managers value and support safe working and are dedicated to workers' safety, hence affecting employees' behaviors and, ultimately, the likelihood of employee injuries. K.H. Hon's study showed that management commitment to safety increased the awareness of workers to safety [42]. K.H. Hon also found a linear relationship between management commitment and accident occurrence. In this regard, K.H. Hon stated, "*The values of the coefficients reveal that for each unit increase in the management commitment score, there is a decrease in the probability of injury occurrence*." The top management, which provides adequate personal protective equipment, first-aid equipment, and trained emergency personnel, has a probability equal to 81.31 of no major or frequent accident occurrence. In addition, the top management that responded to all incidents in a positive, learning way has a less probability of major or frequent accident occurrence with 83.33%. Moreover, if the top management develops a formal safety training program for all new employees, then it has a probability (62.39%) of no major or frequent accident occurrence compared with those who do not have training programs for all new employees. Top management with periodic refresher training for each worker and a formal supervisory safety training program for all frontline supervisors are the most expected to have no major or frequent accident occurrence, with probabilities equal to 52.4 and 62.39, respectively.

The survey result showed the current status of Jordanian construction companies where around 92.2% of companies' top management in the Jordan construction industry has strong core safety values that they comply with, which is considered an outstanding result. Around 83.9% of top management in Jordan provides adequate personal protective equipment, first-aid equipment, and trained emergency personnel. Fortunately, 85.7% of top management in Jordan responds to all incidents in a positive, learning way. Unfortunately, around 35.7% of top management in Jordan did not have a formal safety training program for all new employees. In total, 42.9% of top management had no periodic refresher training for each worker. Additionally, 37.5% of top management did not have a formal supervisory safety training program for all frontline supervisors.

6.3.3. Safety Coordinator/Manager

As for the safety coordinator/manager variables subset, the algorithm achieving the best results was K2+BDeu. The result of this modeling illustrated that the two safety measures, including (1) the safety coordinator/manager is trying to implement accident prevention techniques, and (2) the safety coordinator/manager communicates accident reports to workers to prevent future similar accidents, were the most ones associated with no major or frequent accident occurrence.

The inference in BN results showed that the probabilities of the establishments that did not have a major accident occurrence would be 72.81% if the safety coordinator/manager tried to implement accident prevention techniques and 70.15%, respectively, if the safety coordinator/manager communicated accident reports to workers in order to prevent future similar accidents. These results are understandable when communicating the safety coordinator/manager accident reports with workers; they help workers to understand the causes of accidents and not underestimate how following their roles is related to safety. Furthermore, implementing accident prevention techniques is necessary to remove the risk factors in advance. These views are similar to what previous studies concluded in various countries, including Canada [43], China [44], and Spain [45].

Fortunately, the survey results showed that 76.8% of safety coordinators/managers in Jordan tried to implement accident prevention techniques, and 75% of safety coordinators/managers communicated accident reports to workers to prevent future similar accidents.

6.3.4. Frontline Supervisors

The third model was for the frontline supervisors' variables subset. Both algorithms, K2+MDL and K2+AIC, were elected as the ones that achieved the best results. However, both of these algorithms discovered the same results in terms of which the safety measures most associated with no major or frequent accident occurrence. These safety measures are (1) frontline supervisors encourage the recording and reporting of all near misses, and (2) frontline supervisors are part of the safety procedures reviewing team.

From inference in BN, it was found that the frontline supervisors who reported all near misses would be at 83.33% of no major or frequent accident occurrence. On the other hand, frontline supervisors who are part of safety procedures reviewing would be at 75.49% of no major or frequent accident occurrence. This result is reasonable since safety procedures reviewed by frontline supervisors assess the effectiveness of the current safety, provide effective advice to their establishment on which safety aspects are improving in their future strategies, and provide the chance to select the optimum safety policies for the establishment. This view is similar to the result of K.H. Hon's study, which concludes that frontline supervisors play an influential role in improving safety procedures reviewing and go beyond that to describe frontline supervisors' influences are even greater than senior management in this regard [42]. Fortunately, the survey result showed that around 78.6% of frontline supervisors were part of safety procedures reviewing, and 85.7% of them reported all near misses. However, Oswald, in his examination of the problems with safety observation reporting in the United Kingdom, mentioned that there remained to be the issue of selectively filtering these reports before submission to avoid the allocation of blame or liability and fear of discipline that could alter the results [46]. In addition, the reporting task could capture more of the easily observable safety violations on the site, which was unsurprising to Oswald to find a good number of reports that were focused on just a few areas of poor safety practice.

6.3.5. Workers

Finally, for the workers' variables subset, K2+Bdeu was the algorithm that obtained the best results. The result, according to this subset modeling, showed that safety measures that were most associated with no major or frequent accident occurrence were (1) workers feeling okay to report unsafe conditions, (2) workers' actions suggest that safety training is received well, and (3) workers are part of safety procedures reviewing.

The inference in BN showed that when workers feel okay with reporting unsafe conditions, the probability of having no major or frequent accident occurrence would be 65.68%. Furthermore, when the workers' actions suggest that safety training is received well, and workers are part of safety procedures reviewing, the probability of having no major or frequent accident occurrence would be 63.58% and 70.31%, respectively. These high percentages of having no major or frequent accident occurrence probabilities are understandable since reporting unsafe conditions by workers provides a way to control potential problems before they develop into more serious incidents. Significantly, the workers are the first party who can notice unsafe procedures or equipment on the construction sites. Unfortunately, the survey results showed that 30.4% of workers in the Jordanian construction industry do not feel okay reporting unsafe conditions. In addition, around 32.1% of the results were reported for "workers' actions suggest that the safety training is not received well," and 30.4% of the results were reported for "workers are not part of safety procedures reviewing." This implies that workers cannot share safety information without fear or threat of punitive actions. This is also the case for many workers in the UK construction industry, as Oswald found [46]. Assbeihat mentioned that construction sites had a large number of migrant workers who were non-educated and unskilled, with different behavior toward and beliefs about safety requirements, unstable employment conditions, and work status [27]. The research team can conclude that the reasons behind the workers "do not feel okay reporting unsafe conditions" may include fear of unemployment, non-educated and unskilled workers, and training, not taking into consideration that the construction industry sector in Jordan has migrant workers. These migrant workers face various important challenges as they often do not master the language of the country and may not comply with legal immigration rules. Migrant workers may also be exposed to the riskiest conditions. This view is consistent with what Vignoli found in his study [14]. Finally, this research effort provides evidence of the effectiveness of BN in analyzing construction safety management datasets. It also supports previous researchers' suggestions that BN can be applied to a wide range of problems, ranging from text analysis to problems in medical diagnoses and the evaluation of scientific evidence. They can also be used in modeling uncertain and complex domains such as ecosystems and environmental management [21,22]. However, other probability techniques, including the Markov chain, are worth considering to evaluate their effectiveness in modeling construction safety management datasets.

7. Concluding Remarks and Recommendations

Collaborative efforts should be made a priority of all parties at a construction site to ensure a safe work environment that is free of major or frequent accidents. This study examined the commitment of the construction workforce to fulfill the safety requirements in the Jordanian construction industry, investigated the top safety measures that were associated with achieving no major or frequent accident occurrence, and determined the likelihood of having a construction site free of major and frequent accident occurrence.

BNs models were developed using Hillclimber, K2 search algorithms, BDeu, MDL, and AIC score metrics. It has been concluded that the best algorithms for developing BNs for the variables' subsets of a company profile, top management, safety coordinator/manager, frontline supervisors, and workers are Hillclimber+AIC, K2+AIC, K2+BDeu, both K2+MDL and K2+AIC, and K2+Bdeu, respectively. The results from the evaluation of the BN models show that the top safety measures within each subset of data that are associated with having no major or frequent accident occurrence along with their probabilities are.

- Company profile: The associated factors are: the type of sector and the yearly estimated revenue of the establishment, where the construction of buildings has the highest probability, which equals 46.85%, and establishments with yearly estimated revenue of more than $10 million have the highest probability which equals around 27.5%.
- Top management: The associated factors are: (1) strong core safety values that they abide by, (2) responding to all incidents in a positive and learning way, (3) a formal safety training program for all new employees, (4) periodic refresher training for each worker, (5) a formal supervisory safety training program for all frontline supervisors, and 6) adequate personal protective equipment and first-aid equipment, and trained emergency personnel with probabilities equal to 89.21%, 83.33%, 62.39%, 52.4%, 62.39%, and 81.31% respectively.
- Safety coordinator/manager: The associated factors are: implementing accident prevention techniques and communicating accident reports to workers to prevent future similar accidents with probabilities equal to 72.81% and 70.15%, respectively.

- Frontline supervisors: The associated factors are: encouraging the recording and reporting of all near misses, and the frontline supervisors are part of safety procedures reviewing with probabilities equal to 83.33% and 75.49%, respectively.
- Workers: The associated factors are: feeling okay to report unsafe conditions, workers' actions suggesting that safety training is received well, and workers are part of safety procedures reviewing with probabilities equal to 65.68%, 63.58%, and 70.31%.

In Jordan's construction industry, the top management has an outstanding performance in terms of strong core safety values that they comply with, respond to all incidents in a positive, learning way, and provide adequate personal protective equipment, first-aid equipment, and trained emergency personnel. However, the top management in Jordan does not seem to offer sufficient formal safety training programs for all new employees and/or frontline supervisors nor provide periodic refresher training for workers. The safety coordinator/manager in Jordan performs well in implementing accident prevention and communicating accident reports to workers to prevent future similar accidents. The frontline supervisors in the Jordan construction industry show a strong performance in terms of encouraging the recording and reporting of all near misses and being part of safety procedures reviewing teams. However, there is still a concern about what is reported since reports can be selectively filtered before submissions to avoid the allocation of blame or liability and fear of discipline and legal liability when reporting systems are misused by others. As for workers, it is unfortunate that more than 30% of them in Jordan construction do not feel okay with reporting unsafe conditions; their actions suggest that the safety training is not received well, and they are not part of safety procedures reviewing.

To overcome the aforementioned construction performance deficiencies and shortcomings, this research endeavor recommends that governmental departments give more attention to the implementation of safety requirements in small construction and residential (apartment complexes) and establishments by mandating compliance with more stringent safety regulations and requirements through inspection and enforcement. Furthermore, it is recommended to establish safety-focused prequalification criteria for selecting and awarding contractors. In addition, top management must prioritize safety, develop safety training programs for all employees and frontline supervisors, and periodically offer refresher training workshops. Furthermore, it is recommended that the recruitment of a full-time safety coordinator/manager for construction sites become a mandatory requirement by the government. Furthermore, adopting continuous safety improvement processes and blameless safety culture is recommended to provide a safe workplace. Moreover, this study recommends the use of safety rewards and incentive schemes to encourage the workers to be a part of safety procedures reviewing teams and creating penalties for worker safety violations. More training should be conducted, considering that the construction sector in Jordan has a large number of migrant workers, which may require some customization of safety training modules and workshops. Finally, improving safety and health awareness among workers, having mandatory safety training courses for all site personnel organized by training providers that are approved by the government, providing in-house training and orientation courses to all workers working by the company itself, providing the workers with toolbox training on how safety is applicable to their particular scope of work, and awarding a certificate to those who pass the required safety tests can be additional effective strategies to creating a safe workplace.

This research effort contributes to the body of knowledge by effectively understanding the top safety measures associated with reducing accident occurrence in the Jordan construction industry. Providing decision-makers with insights into individual workforce safety performance deficiencies is essential for creating a safer work environment and preventing work accidents. Furthermore, this work offers decision-makers some efficiency benchmarks that help in providing valuable future comparisons and feedback for improving workforce safety performance. While the context in this paper is the Jordanian construction industry, the novelty of the work lies in the BN modeling methodology and recommendations that any country can adopt for evaluating the safety performance of its construction industry.

This research endeavor is, therefore, a significant step toward providing knowledge about the top safety measures associated with reducing accidents and establishing efficiency comparison benchmarks for improving safety performance.

This research, however, had some limitations that should be noted. The collected data had mainly come from large construction establishments, resulting in outcomes that might be skewed toward construction safety in large firms. Most of the study sample is from general contractors presenting a better safety performance than what we expect from the total industry players, such as subcontractors and specialty contractors. Future studies must focus on strategies to build samples that better represent the whole industry. This study also mainly focused on results based on survey data from experts and has not studied the actual injury and fatality databases. Therefore, this study is expected to be correlated with Jordan's injury and fatality databases. Additionally, the survey in this study was distributed by electronic mail to top management representatives, frontline supervisors, and safety coordinator/manager and did not include workers. Therefore, future studies could address this issue.

Author Contributions: Conceptualization, M.A.-K. and O.A.; methodology, M.A.-K., R.O.M. and O.A.; validation, H.L. and A.A.; formal analysis, M.A.-K., R.O.M. and O.A.; investigation, M.A.-K., O.A. and H.L.; resources, A.A.; data curation, M.A.-K. and R.O.M.; writing—original draft preparation, M.A.-K.; writing—review and editing, O.A. and H.L.; visualization, A.A.; supervision, M.A.-K. and O.A.; project administration, M.A.-K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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