A Fault Tree Analysis (FTA) Based Approach for Construction Projects Safety Risk Management

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Abstract

Managing safety risk on construction projects represents the mainstay for projects' success. In fact, by avoiding accidents, all the related direct and indirect costs and delays can be prevented. However, because of construction projects inherent characteristics, many unplanned events may occur. Therefore, understanding accidents occurrence comportment seems to be the most important Construction Management challenge.

Different methods have been developed for accidents risk prediction such as Risk Assessment, but they are always confronted to the reality of the construction industry. In addition, these methods are not systematically taking into consideration human behavior factor, which is far from being modelizable by simple linear mathematic models. As an alternative, a concept that combines Fault Tree Analysis and Task Analysis is proposed in this study. This method considers construction site as a complex system in which failures may occur. The root causes of these failures will draw Fault Trees that can be used for probabilistic qualitative and quantitative simulations. The aim is to develop a customizable decision support tool able not only to alarm against the risks of accidents, but also to give recommendations for actions that can be implemented in order to minimize accidents occurrence probability.

Keywords: Construction; Project Management; Health & Safety; Risk; Fault Tree Analysis.

1. Introduction

Construction sites safety risk management becomes increasingly a subject that spills ink every time an accident is announced. In fact, every accident has a negative effect on the project it occurs in, and affects directly and indirectly costs and durations. That makes the determination and control of factors responsible for site accidents the first step for project success. Through this research, we are contributing to the Safety Risk Management body of knowledge by addressing the following research questions (RQ):

RQ1: How construction site inherent characteristics can influence accidents occurrence risk?

RQ2: What makes the classical methods of Safety Risk assessment unable to detect all accidents?

RQ3: Considering construction projects complexity, how can Fault Tree Analysis (FTA) contribute to have a more reliable Safety Risk assessment method?

The paper starts with an overview of the relevant literature in relation with Construction projects Safety Risk management and construction sites inherent characteristics that have direct influence on this risk. Followed by a dedicated paragraph to discuss the concept of complexity and its relationship with construction projects. Afterwards, the Fault Tree Analysis (FTA) method is presented in section 3 and Construction Safety Fault Tree is visualizedin section 4. After that, the way qualitative and quantitative analysis can be performed on Safety Fault Tree is discussed in section 5. This discussion in based on a case study related to on-site lifting operations failures.

2. State of art

2.1. Construction projects Safety risk management

Workplace accidents continue to represent a significant issue within the construction industry. Researchers address this topic in many ways such as Accident Analysis Studies, Accident Prevention Studies, and Accident Risk Management Studies.

Accident analysis studies can be rooted in the works of Heinrich (Heinrich 1930), Leplat (Leplat 1978), and Kjellen and Larsson (Kjellen and Larsson 1981). This category includes also accident causation models such as DeJoy's(DeJoy 1990), Abdelhamid and Everett's(Abdelhamid and Everett 2000), Suraji's(Suraji, Duff, and Peckitt 2001), Leveson's(Leveson 2004), Dekker's(Dekker 2016), Hollnagel's(Hollnagel 2012). The most recent model was based on a review of applied accident causation models and contributing factors in construction projects. In this publication,Woolley (2019) revealed that contemporary models of accident causation have not yet been applied in construction-related research, and that the models and methods applied in the construction literature give importance to company, management, and front line work levels rather than considering broader, construction projects system-wide factors (Woolley et al. 2019).

Accident Prevention Studies are, on the one hand, statistical analysis of accidents performed by Hinze (J. Hinze 1996), Huang and Hinze(X. Huang and Hinze 2003), López Arquillos et al.(Arquillos, Romero, and Gibb 2012), Byung Wan et al.(Jo et al. 2017). On the other hand, there are studies under this category that analyzed the economic cost of accidents like what was performed by Leopold and Leonard(Leopold and Leonard 1987), Waehrer et al.(Waehrer et al. 2007), Theo et al.(Haupt and Pillay 2016).

Safety risk management studies are based on the fact that complete elimination of Safety Risk in construction sites is an unachievable goal (perfect safety would require stopping all the construction activities) as not all risks can be removed and not all possible risk mitigation measures are economically practical. That means it is tolerable that there will be some residual risk of harm to people, property or environment.

Safety risk management requires a consistent process of objective analysis for identifying and evaluating risks. It is the results of a structured approach and systematic actions aimed to achieve the balance between assessed risk and practicable risk mitigation. It consists of three essential elements:

- **Hazard identification:** identification of undesired or adverse events that can lead to hazard occurrence and the analysis of mechanisms by which these events may occur and cause harm.
- **Risk assessment:** identified hazards are assessed in terms of criticality of their harmful effect and ranked in order of their risk-bearing potential. The severity of consequences and the probability of occurrence of hazards are determined. If the risk is considered acceptable, construction activity continues without any intervention. If it is not acceptable, the risk mitigation process is engaged.
- **Risk mitigation:** if the risk is considered unacceptable, then control measures are taken to eliminate, substitute, enforce engineering solutions, establish administrative control or, as last alternative, utilize personal protective equipment (PPE).

Haslam et al. (2005)identified that one of the most relevant underlying factors of about 84% accidents is the lack of appropriate Safety risk management (Haslam et al. 2005). Indeed, these accidents could have been predicted and avoided if Safety risk management had been properly carried out. The absence of adequate risk management process can be explained by the absence of technical skills, information and documentation, and lack of financial resources. In fact, in the majority of cases, companies choose to perform Safety risk management not as an important and necessary process before starting the construction activities but to be aligned with the increasingly demanding legislation and regulations. That is confirmed by Wilson and Koehn (2000) who highlighted that, in the majority of the companies, Safety management is implemented in order to limit the responsibilities and costs associated with accidents and health problems (Wilson and Koehn 2000).

The existing literature about Safety risk management process shows that the evaluation approaches of hazards several similarities. In fact, it is usual to find references, such as HSE (H.S.E. 2001) and ISO (ISO 2018), that define common criteria for Safety risk analysis. It is also common that this process takes place during the design stage in order to implement efficient control measures before even the beginning of construction activities (J. Hinze and Wiegand 1992)(Smallwood 1996)(Suraji, Duff, and Peckitt 2001)(Gambatese, Behm, and Hinze 2005)(Behm 2005)(Gambatese, Behm, and Rajendran 2008).

However, in many cases, even if a Safety risk management process is implemented, the complete avoidance of on-site accidents stays unachievable. The reason is deeper than the impossibility of removing all risks or the economic cost of such actions. Indeed, Safety risk assessment does not guarantee the identification of all workplace risks. In other words, there are unknown risks, acceptable or not, that may cause harm to people, property or environment. Without speaking about the reality that the risk assessor, as human being, is subjective by definition and can be mistaken, many publications attempted to explain that through outlining construction projects inherent characteristics such as:

- **Construction industry fragmentation:** which is the result of construction projects execution structure that involves many parties (architects, engineers and other professionals). These can have different, sometimes conflicting, Safety objectives (Tatum et al. 2000)(Alashwal et al. 2015)(Gambatese 2006)(Saunders et al. 2017).

- **Dynamic construction environment:** unlike the other industries, construction environments are dynamic systems, in which the relationships between project goals (e.g. time, cost, quality, safety etc.) and resources (e.g. material, labor, finance, etc.) are in constant change (Love et al. 2002). They are exposed to uncontrolled factors (e.g. weather conditions, site location, workers turnover, decision makers etc.) that can vary from previous projects (Humphrey et al. 2004)(Jensen et al. 2011). Obviously, the priority that project stakeholders place on Safety and other project goals can change across a single project's life (Humphrey et al. 2004)(Y.-H. Huang et al. 2007). These factors undoubtedly contribute to accidents occurrence probability (J. W. Hinze 1997)(J. Hinze and Wilson 2000)(Carter and Smith 2006)(Yi and Langford 2006).
- **Construction industry culture:** Schwatka et al. (2016) conducted a literature review about factors influencing Safety culture and found that within the wide range of indicators used to measure Safety climate, policies, procedures, and practices were the most common, followed by general management commitment (Schwatka et al. 2016)(Andersen et al. 2018).
- **Individual inherent characteristics:** accidents often happen because of people's physical or mental unsuitability due to a lack of attention, carelessness, or a lack of appropriate training and supervision (Misiurek et al. 2017). Besides, employers' and employees' attitudes and behaviors can negatively influence Risk perception and increase accident occurrence probability(Nielsen 2014)(Perlman et al. 2014).

Provided all the outlined construction sites inherent characteristics, the concept of construction "complexity" seems to be an important part of the problem. In fact, construction project can be seen as a "structure with variations", which is exactly the definition of a "complex system" as per Goldenfeld and Kadanoff (Goldenfeld and Kadanoff 1999). So, is construction project really a complex system?

2.2. Construction and complexity

Construction industry is considered as the most complex compared to any other industry. That made many Scientifics attempt to understand construction projects complexity (Baccarini 1996)(Bertelsen 2003)(Sven Bertelsen 2003)(Qureshi and Kang 2015). Actually, there is a sort of consensus that construction should be seen as a complex dynamic systemas per the following three axis:

- The construction process, which is composed of three different perspectives: transformation, process & value generation.
- The production system, which the role is played by the different construction firms, teams… etc.
- The social system constituted principally by human resources that work in construction workplaces.

Considering construction projects as complex systems is consistent with complexity definitions. In fact, based on the outlined construction inherent characteristics, it can be accepted that construction project is "literally one in which there are multiple interactions between many different components." (Rind 1999). It can also be considered that construction, as a complex system, "is one whose evolution is very sensitive to initial conditions or to small perturbations, one in which the number of independent interacting components is large, or one in which there are multiple pathways by which the system can evolve. Analytical descriptions of such systems typically require nonlinear differential equations" (Whitesides and Ismagilov 1999). This non-linearity can explain why using classical methods of construction Safety risk assessment is far from being correct because, in this way, assessors are trying to model construction complex paradigms using simply linear equations with few variables. Many scientists tried to model construction complexity using different dimensions including structural complexity, uncertainty, safety and socio-political (Geraldi, Maylor, and Williams 2011). Vidal et al. (2008) developed a model that identifies, defines and models complexity within the field of project management (Vidal and Marle 2008).

In short, in order to build a stronger method for construction Safety risk management, construction must be seen as a complex system. This new approach will consider, first, that the evolution of this system is linked to the evolution of its components as autonomous agents. Second, analytical description of this system is always nonlinear differential equations. Third, having an exact description of such a kind of systems is impossible because of the existence of undefined values. In this paper, this new approach will be developed using lessons learned from industrial complex systems analysis approaches. These approaches use qualitative and quantitative probabilistic methods to model the interactions between complex system elements. In fact, one of the most reliable methods, already tested and well developed for the study of complex industrial systems is Fault Tree Analysis (FTA). This method will be used in order to introduce a new way of Safety risk evaluation that can be adopted by construction projects.

3. Methodology: Construction Safety Fault Tree Analysis (FTA)

3.1. Overview

The development of industrial complex systems reliability, maintainability, availability and safety studies has given birth to many methods known by their accuracy including fault tree analysis, event tree analysis, and reliability block diagrams. All these methods represent, at best, approximations to the system reality due to the number of autonomous agents that should be tracked in the same time, the existence of undefined values, and especially the fact that complex systems are not modelizable using linear equations (Sven Bertelsen 2003)(Qureshi and Kang 2015). That why, the larger the method is in terms of complex system inputs, the more useful it is in terms of insights for prediction of eventual failures (Rausand and Høyland 2004).

The Fault Tree Analysis (FTA) is an engineering technique that is widely used in complex systems safety and reliability studies. This method consists in graphically representing the possible combinations of events that allow the occurrence of an undesired event. A tree is thus build based on successive levels of events that are articulated through logic gates. By adopting this representation and using a deductive logic based on the Boolean logic, it is possible to go back from the effects of the undesirable event to basic events, independent of each other, but above all, probabilizable (Berk 2009)(Tanaka et al. 1983). Fault Trees were introduced for the first time by Bell Labs in the 1960s (Lee et al. 1985).

3.2. Definitions

Basic events: they can be or failure or normal events such as events that describe a normal system state, a normal operation or function … The basic events are characterized by a probability function.

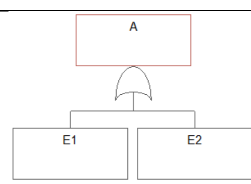
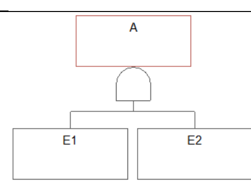
Gate events: they are logic operators combining inputs in the fault tree nodes. The logic operators used are AND, OR, NAND, NOR, and K of N gates predominating.

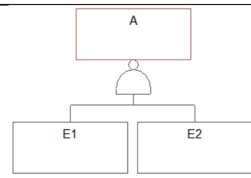
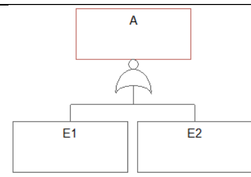
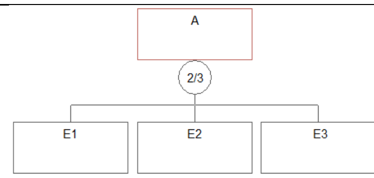
Transfer events: They are pointers to a tree branch and indicate a subtree branch that is used elsewhere in the tree. The transfer is for several purposes:

- Plots organization
- Indication of tree branches that are used numerous times
- Use of modules from separate analysis

Logic operators: The table 1 presents logic operators used for Fault Tree constitution.

Table 1. Fault tree logic operators

Logic operator	Definition	Representation	Probabilistic formula
Or	The output event appears if at least one of the input events appears.		$P(A) = P(E1) + P(E2)$ (1)
And	The output event appears if all input events appear.		$P(A) = P(E1)\,P(E2)$ (2)

Nand	The logical state of the output is the opposite of the And logic		P(A) = 1 - P(E1) P(E2) (3)
Nor	The output event appears if only one entry event appears		P(A) = 1 - P(E1) - P(E2) (4)
K/N	The output event appears if at least k input events appear (k <n)		P(A) = P(E1)P(E2) + P(E1)P(E3) + P(E2)P(E3) (5)

3.3. Accidents as failures in construction projects complex systems

Managing Safety Risk on construction projects represents the mainstay for projects' success and the objective of every project manager. In fact, by avoiding accidents, all the related direct and indirect costs and delays can be prevented, especially that the majority of these costs are uninsured. The table 2 gives examples of direct and indirect costs related to construction accidents.

Table 2. Construction sites accidents direct and indirect costs

Construction sites accidents direct costs	Construction sites accidents indirect costs
Fines in the criminal courts	Loss of staff moral
Compensation payable to victims	Time lost for accident investigation
First aid treatment cost	Cost of remedial actions after accident investigation
Worker sick pay cost	Cost of making available a temporary replacement for the victim
Repairs of damaged equipment	Eventual delays causing loss of goodwill with clients
Lost construction site production while dealing with the accident event	Delays which can cause activation of penalty contractual clauses
Costs related to the rehabilitation of the injured	Damage to company reputation

Considering construction accidents as complex system failure is not a new idea. In fact, an analogy can be made between construction site accidents as failure in the complex system and the Reason's 'Swiss cheese' model (Bakeli and Alaoui 2018). This last outlined a combined effect of various factors on different levels that are responsible for accidents, called by Reason 'latent condition pathways'(J. T. Reason 1990). Indeed, to understand that, Reason imagined slices of Swiss cheese placed side by side. Every slice is one of the factors levels. The 'latent condition pathways' are gaps or holes that are, in reality, circumstances with risks and safety outcomes caused by certain factors in certain levels: organizational level, managerial level, work level, precondition level…. Reason defines the concept of accidental trajectory as being the trajectory on which the holes of each level are aligned. Therefore, in the same way, accidents will be studied as failures caused by interaction between certain factors in certain levels that will be called later "basic events". That will not be performed without taking into consideration human behavior, which is far from being modelizable by simple mathematic models.

3.4. Construction Safety Fault Tree representation

In order to represent Construction Safety Fault Tree, it is necessary to identify the Top event, which is the failure or the undesired event of the complex system. In this case, the Top event will be "accident" which is defined as any unplanned event that results in injury or ill health of people, or damage or loss to property, plant, materials or the environment or a loss of a business opportunity (HSE n.d.).

The representation of the Fault Tree will be using one of the most reliable specialized software, which is Arbre-Analyste. Indeed, this is a new free tool for Fault Tree building and analysis that allows to edit, display, calculate, process calculation results and export fault trees to different market modeling tools(E. Clement et al. 2014). It is based on: the Open-PSA format (PSA n.d.) and the XFTA calculation engine(A. Rauzy n.d.). This tool will allow, not only to represent Construction Safety Fault Tree and Fault Subtrees, but also to proceed to qualitative and quantitative analysis, namely:

- Identification of cut sets which are sets of basic events whose (simultaneous) occurrence ensures that the TOP event occurs.
- Identification of minimal cuts: a cut set is said to be a minimal cut set if, when any basic event is removed from the set, the remaining events collectively are no longer a cut set.
- Calculation of TOP event probability.
- Calculation of minimal cuts probability.
- Calculation of the importance factors of the basic events;
- Sensitivity studies via Monte-Carlo simulations.

4. Results: Construction Safety Fault Tree

4.1. Construction Safety Fault Tree and Fault Subtrees

The Construction Safety Fault Tree presented in figure 1 is based on four important sources of information:

1- The Construction Safety Fault Tree is built in accordance with the international systems of construction sites events codification. In fact, it was chosen to follow the Occupational Injury and Illness Classification System (OIICS) trees developed by The National Institute for Occupational Safety and Health (NIOSH) (NIOSH 2019). According to this classification, construction site accidents are composed to 7 families presented in Figure 1:
   - Failures related to contact with objects and equipment
   - Failures related to Falls
   - Failures related to bodily reaction and exertion
   - Failures due to exposure to harmful substances and environments
   - Failures due to work related transportation
   - Failures related to fires and explosions
   - Failures related to assaults and violent acts

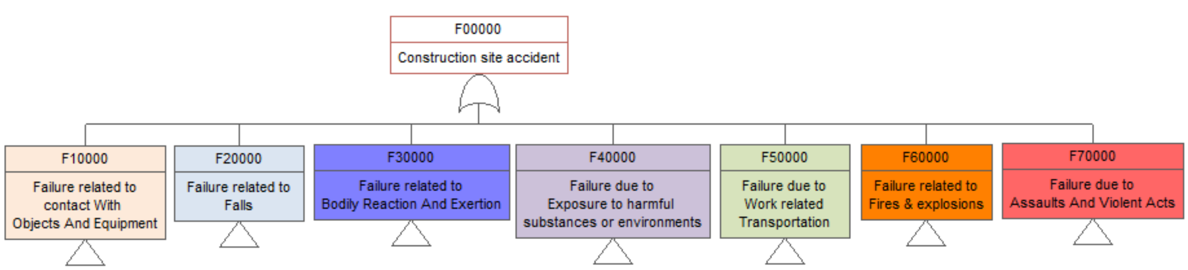


Figure 1. Construction Safety Fault Tree

2- Fault Subtrees development is based on Job Hazard Analysis, which is a technique that focuses on job tasks as a way to identify hazards before they occur. It focuses on the relationship between the worker, the task, the tools, and the work environment(OSHA 2002).

3- Job Hazard Analysis is completed with referenced technical documentation developed by international safety organisms such as the national safety council (NSC) (National Safety Council (NSC) 2019), Occupational Safety and Health Administration (OSHA) (OSHA 2019), Safety Executive (HSE) (HSE 2019b), INRS (INRS 2019), The National Institute for Occupational Safety and Health(NIOSH 2019)…
4- The developed Fault Tree could not stay in the theoretical level. That why it was necessary to look for real construction sites data in order to confirm the logic used and especially the basic events. It was chosen to use data from Fatality Assessment and Control Evaluation (FACE) program.Fatality Assessment and Control Evaluation (FACE) program (NIOSH 2019) is a research program designed to identify and study fatal occupational injuries. One of the goals of the FACE program is the identification and the investigation of work situations that led to fatalities.The Construction FACE Database (CFD) is a database in Excel created by Center for Construction Research and Training CPWR (CPWR 2019) to facilitate use of the information provided by the Fatality Assessment and Control Evaluation (FACE) reports. The investigation results in FACE reports provide information on the circumstances surrounding work-related fatalities on construction-related fatalities (total of 768 deaths) that were recorded from 1982 to 2015.

4.2. Effect of the human error
Human resources are one of the most important elements of the construction site system. The fact of considering individuals as similar from site to site will cause a big limitation to the proposed method of accident analysis. In fact, human error is an important dimension that shall be taken into consideration. That is confirmed by many studies that worked on human reliability, interactions between people, organizations, management and cultures (J. Reason 2000)(French et al. 2011), impact of training on human error(Mollo, Emuze, and Smallwood 2018).
For that purpose, a special Fault tree was created based on special basic events: non-material basic events covering aspects related to human personality, job complexity and organization failure. The organization of this fault tree is taking into consideration human failures types (Mollo, Emuze, and Smallwood 2018) shown in figure 2.
That will ensure that human error impact will be considerable depending on the characteristics of human resources of each construction sites. An effect that will have an impact on many levels of Top event probability calculation.

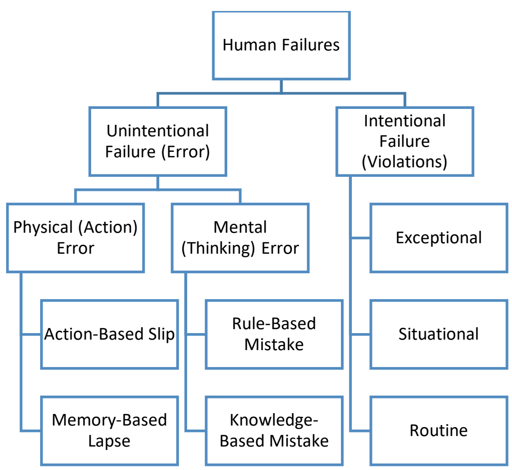


Figure 2. Types of human failures

5. Discussion: Qualitative and quantitative analysis using Construction Safety Fault Tree - lifting operation case study

5.1. Failure in lifting operation Fault Subtree

This paragraph will study an example of Fault Subtrees: Failure in lifting operation Fault Subtree presented in Figure 3 which is part of the branch "Failure related to contact with objects and equipment" of the Construction Safety Fault Tree. This Fault Subtree is constituted of 24 basic events and 3 transfers to other subtrees such as Manual handling subtree and Human error subtree.

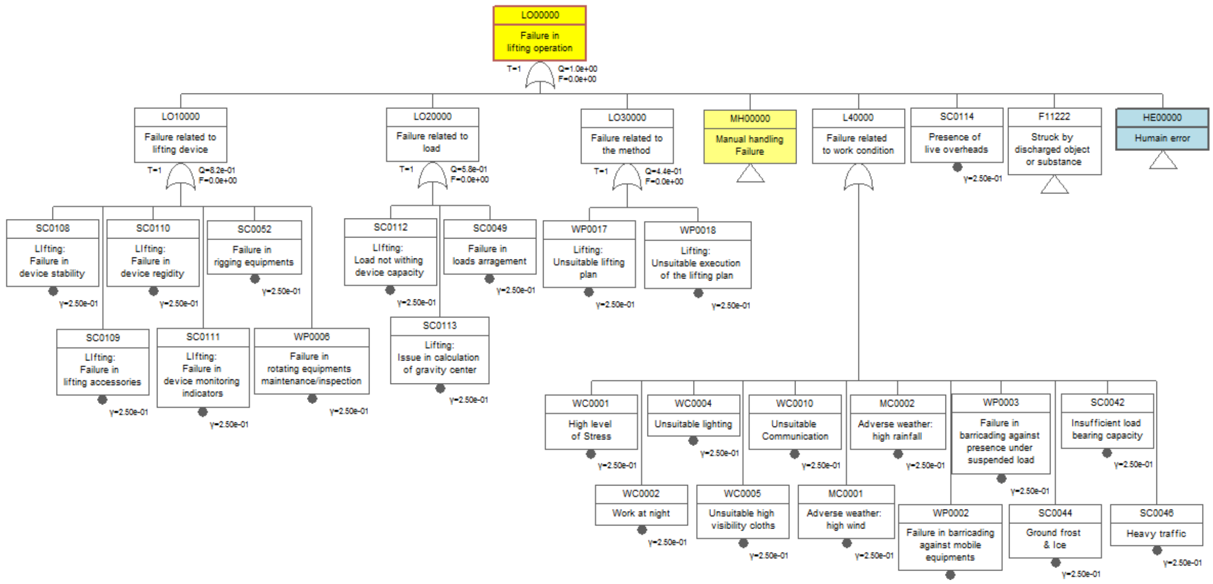


Figure 3. Failure in lifting operation Fault Subtree

5.2. Exploitation of Failure in lifting operation Fault subtree

5.2.1. Case study assumptions

Failure in lifting operation Fault Subtree comportment will be studied considering different configurations as presented in table 3.

Table 3. Case study assumption

Basic events	Construction site with no failures in basic events (theoretical assumption)	Same construction site with change on one basic event	Same construction site with failure on many events
	-	High wind	Relative failures
Lifting: Failure in device stability	0	0	0
Lifting: Failure in lifting accessories	0	0	0.1
Lifting: Failure in device rigidity	0	0	0
Lifting: Failure in device monitoring	0	0	0
Failure in rigging equipment	0	0	0.1
Failure in rotating equipment maintenance/inspection	0	0	0.2
Presence of live overheads	0	0	0
Lifting: Load not within device capacity	0	0	0
Lifting: Issue in calculation of gravity center	0	0	0
Failure in loads arrangement	0	0	0.1
Lifting: Unsuitable lifting plan	0	0	0
Lifting: Unsuitable execution of the lifting plan	0	0	0
High level of Stress	0	0	0.1
Work at night	0	0	0
Unsuitable lighting	0	0	0
Unsuitable high visibility cloths	0	0	0
Unsuitable Communication	0	0	0

Adverse weather: high wind	0	1	0
Adverse weather: high rainfall	0	0	0.1
Failure in barricading against mobile equipment	0	0	0
Failure in barricading against presence under load	0	0	0
Ground frost & Ice	0	0	0
Insufficient load bearing capacity	0	0	0
Heavy traffic	0	0	0

5.2.2.Qualitative &Quantitative analysis

Considering the case of construction site with no failures in basic events (theoretical assumption), it will be logic that the probability of occurrence of a failure related to lifting operation will be 0, that is confirmed by the calculations.

The second case will consider a change in one basic event(occurrence of adverse weather, high wind for example). Calculations show that failure related to lifting operation probability will become 1. That means that the fact of not stopping lifting operations in case of high wind will automatically cause an accident. In addition, minimal cut analysis shows that high wind event does not need any other basic event to cause accident.

The third case is more representative of the reality: many events are having failures with a defined occurrence probability. For this case, failure related to lifting operation probability will be 0.528. That means that every two lifting operations, an accident can occur. In addition, the probability is a result of many relatively unlikely basic events. The table 4 presents minimal cuts to be considered with their probability of occurrence. For lifting operation Fault Subtree, all minimal cuts are order 1.

Table 4. Minimal cuts analysis

N°	Order	Probability	%	Description
1	1	0.2	28.6%	Failure in rotating equipment maintenance/inspection
2	1	0.1	14.3%	Lifting: Failure in lifting accessories
3	1	0.1	14.3%	Failure in rigging equipment
4	1	0.1	14.3%	Failure in loads arrangement
5	1	0.1	14.3%	High level of Stress
6	1	0.1	14.3%	Adverse weather: high rainfall

6. Conclusions and perspectives

Overall, the contribution of this paper to Safety risk management body of knowledge is three-fold: first, an attempt to correlate accidents occurrence risk with construction site inherent characteristics. Second, a proposed explanation, based on construction inherent characteristics, of the reason why the classical methods of Safety Risk assessment are unable to detect all accidents. This explanation has given the opportunity to introduce system complexity as a concept that can be adopted for construction projects, and to use Fault Tree Analysis (FTA) analysis as a new, and more reliable, way to perform Safety Risk assessment. A method that considers construction site as a complex system in which failures may occur. The root causes of these failures will draw Fault Trees that can be used for probabilistic qualitative and quantitative simulations.

In fact, this opens new horizons for the application of reliable methods, already tested and well developed in the industrial domain for construction Safety risk management. This is also consistent with the sense that construction is nothing but an industry and that construction site is a complex system in which human, material and financial resources are interacting independently but with a direct effect on the whole system. Fault Tree Analysis (FTA) is a considerable step towards the adoption of a new concept of Safety risk management that is able to coexist with construction inherent characteristics. A concept that is invariable from risk assessor subjectivity and ready to model more appropriately the effect of human error, to predict accidents before they happen, and to prescribe the necessary actions to be performed in order to reduce accidents risk.

In parallel, many perspectives will be open. First, the development of Fault Subtrees able to cover all the construction sites risks, especially risks that are still not developed. Then, the work on basic events probability functions especially that the existing software are able to perform complex calculations using probabilistic functions such as Exponential function, Weibull function... At the end, it seems likely to assert that the presented method can be exported to other project risk management subjects such as quality, environment, financial risks…That will be studied in future papers.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

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