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Exploring associations between resilience and construction safety performance in safety networks

Farah Wehbe, Malak Al Hattab, Farook Hamzeh *

Dept. of Civil and Env. Eng., American University of Beirut, Lebanon

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A B S T R A C T

Safety management plays a major role in construction as negligence may result in loss of lives and detrimental project consequences. The Middle East witnesses poor safety management where companies need to improve their performance instead of hiding their deficiencies. This study aims at evaluating safety performance and network resilience to risks by studying safety-related interactions among the construction team. Safety on three mega-projects is evaluated by analyzing their respective networks for communication and safety management and mapping them using Gephi. Using Social Network Analysis (SNA), visualizations and various metrics were computed revealing network characteristics and communication patterns. Resilience metrics were measured using actual safety performance data and overall network resilience was simulated through agent-based modeling using NetLogo. Results and correlations show that networks with better interaction and structure have higher resilience to prevalent risks and have better actual safety performance.

1. Introduction

Safety performance remains the top concern of project managers as poor safety increases project failures and impacts all other Key Performance Indicators (KPI). For instance, unsafe work environment will undermine the quality of work and consequently incur additional time and subsequent costs to cater for such conditions. Safety remains marginalized in the Middle East, leading to high accident rates with a number of undisclosed incidents. The work environment is described as a place where “no international safety and health standards currently exist” (Kenrick, 2012). The construction industry in the region has been growing significantly over the last years and is expected to provide projects worth 500 billion dollars by 2015 (Kenrick, 2012). In Qatar, where construction work is booming in preparation for the 2022 World Cup, the fatality rate is around eight times as high as the UK (Sultan, 2013). Contracting companies need to improve safety management practices to reduce the current rate of injuries. Researchers have been studying safety practices but are faced with lack of accident reporting and absence of safety records. However, it is important to distinguish between two interpretations of what accident reporting value indicates. On one hand, a greater number of incident reports can be a result of improved reporting culture, and on another hand, it can be a result of an increase in reportable events and accidents. Moreover, the reporting frequency does not necessarily reflect the severity of incident cases, where an increase in reporting can a result of frequently occurring incidents with low consequences and not necessarily cover more severe incident occurrences.

Construction projects are known for having inherent risks with high levels of uncertainty. Risks vary with project complexity but remain inevitable; hence safety and risk management should be more emphasized on construction projects. To improve safety performance and implement proper risk management on a project, it is important to track how people interact with each other and how they deal with unfavorable conditions that jeopardize the work environment.

Safety management and risk analysis in practice are normally handled as isolated occurrences without accounting for root causes or investigating the phenomenon within an interactive human network. Construction and project managers require all individuals to undergo safety training and that incidents and safety issues be reported. However, such data needs not only be reported and statistically summarized, but also necessitates that improvements and prevention measures be employed. Alsamadani et al. (2013) used SNA to study safety communication in small work crews in the US by looking at safety performance of different crews, investigating socio-grams, and detecting communication patterns

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* Corresponding author at: 406 E Bechtel, American University of Beirut, Riad El Solh-Beirut 1107 2020, Lebanon. Tel.: +961 1 350000x3616; fax: +961 1 744462.

E-mail addresses: faw01@aub.edu.lb (F. Wehbe), mja28@aub.edu.lb (M.A. Hattab), Farook.Hamzeh@aub.edu.lb (F. Hamzeh).

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visually. However, their data analysis suggests that the general SNA metrics are not significant measures that distinguish high from low performing crews. This study challenges the last finding and introduces the concept of resilience to differentiate robust networks from weak ones.

Available literature on SNA and safety studies are limited to examining communication patterns across social networks and their safety performance. However, this limitation in research does not assist in proactively managing risks and safety matters, where understanding a network's behavior and readiness to prevent risks and be robust against hazards is of ample importance. Therefore, to address this limitation and fill the gap in knowledge, this study provides a new perspective on safety management in social networks by evaluating safety performance and assessing the system's resilience to prevalent risks.

In this regard, this research employs SNA to map the network of people and their communication patterns on a project and looks at different metrics to evaluate system resilience which describes the ability of the system to avoid failures as well as to recover quickly once they occur. Results from this study can assist construction managers in understanding the importance of communication patterns for proper safety and risk management. The contributions of this paper is in relating communication networks to network resilience and safety performance. Safety management is presented and demonstrated through case studies as a social collective effort that relies on proper communication among the network of people within an organization.

2. Background

2.1. Safety management

Safety is a critical performance indicator as it reflects work conditions, injuries, and the loss of human lives which impacts project duration, cost, and quality. Hence, monitoring safety should be integrated at all stages of the project. As "you can't manage what you can't measure", proper safety management requires the tracking and monitoring of several safety performance indicators to enable the identification of safety issues, continuous improvement of work processes, and better accident prevention measures.

Various indicators are used to measure safety performance: the Occupational Safety and Health Administration (OSHA) recordable incident rate (RIR), the DART injury rate which stands for "days away, restricted, or transferred" work, and other measures that contractors use as benchmarks to assess their overall safety performance. In fact, the records of OSHA rates show that the construction industry has significantly improved in terms of safety performance between 1989 and 2009. However, an interesting observation is that the rate of improvement has declined since 1998 (Hinze et al., 2013).

As safety management dictates policies and practices that help reduce hazards on a project, the production control system establishes process planning and decisions to ensure a safe work environment (Mitropoulos, 2012; Hinze, 2002a; Aslesen et al., 2013). A model integrating safety job analyses in the Last Planner System (LPS) helps reduce hazardous situations by allowing the detection of these early on. Wehbe and Hamzeh (2013) also suggest the integration of Failure Mode and Effect Analysis (FMEA) at the look ahead planning level of LPS as a risk management practice that avoids the emergence of safety hazards. Alarcon et al. (2011) identify seven safety practices that are statistically significant to reducing accident rates, such as accident and incident reporting, management commitment, and safety incentives.

The safety culture is perceived as a social and collective effort (Aslesen et al., 2013) and hence, the network of people (including communication patterns) in a company is a determining factor that reflects how the system performs. This is where SNA helps map the project network for further research and analysis.

2.2. Social Network Analysis (SNA)

Social Network Analysis is an effective method for analyzing social interactions among individuals and organizations which can be used to reveal the underlying mechanisms and dynamics driving such relationships within complex systems (Easley and Kleinberg, 2010). Nodes represent individuals within the network and ties represent associations between those individuals. Visualization of the network is crucial to the understanding of network data and quantitative metrics allow further analysis of hidden behaviors (Wasserman and Faust, 1994).

Social network theory has been applied in several fields such as sociology, anthropology, economics, biology, tele-communications (Zhu et al., 2012; Aral et al., 2009), and has extended beyond social sciences. In design and construction, SNA was primarily implemented to discuss information flow among project participants and optimize communication and transparency (Alarcon et al., 2013; Hickethier et al., 2013; Chinowsky et al., 2010). It has also been used to analyze the benefits of Building Information Modeling (BIM) and lean practice on design error management (Al Hattab and Hamzeh, 2015). The success of projects is hence not only associated with optimized project management practices but also with the performance of project teams and their level of communication.

This research approaches safety through social network theory and studies the network of people involved in safety issues on construction projects. A recent study by Alsamadani et al. (2013) explores safety communication in small work crews using SNA. Safety performance of different crews is measured using communication patterns in socio-grams, and is then compared against maximum performance. However, data analysis suggests that the resulting SNA metrics other than density are not significant measures to categorize crews. This paper therefore expands on previous research to show that SNA metrics can actually be used as leading indicators for safety performance.

Hence, the objective of this research is to evaluate safety performance through mapping interactions regarding safety matters, and to reflect on the system's resilience to prevalent risks. After mapping the social network model, different network metrics are retrieved and associated with safety indicators; these include:

(1) *Node-specific metrics: Average Degree Centrality* which measures the number of links an individual has with others where a higher number indicates more connections and more influence an individual has on a network, *Betweenness* which measures the number of node pairs that an individual connects or bridges (serving as a broker or intermediary) where a higher value indicates a higher influence of this individual and his power to control flow and interactions (Hickethier et al., 2013), and *Closeness* which measures the total number of links from an individual to others where a lower value indicates that an individual is more reachable by others (Haythornthwaite, 1996; Kim, 2007).

(2) *Network-specific metrics: Density* which reflects how well-connected and cohesive a network is by measuring the number of existing links between individuals and dividing it by the number all possible links where a higher ratio value indicates a well-connected and interactive network (Alarcon et al., 2013), *Average Path Length* which measures the average number of links individuals require to reach each other where a smaller value is a better reflection of connectivity and faster interactions (Haythornthwaite, 1996), *Clustering*

Coefficient which measures how clustered individuals are and indicates the existence of isolated separate groups (Hickethier et al., 2013), and *Resilience* which estimates, in this study, the ability of the system to respond to incidents and recover from damages.

2.3. Network resilience and risk management

Resilience engineering is a paradigm for safety management that focuses on how people cope with complexity under pressure to achieve success (Wybo et al., 2006; Resilience Engineering Network, 2008). Wreathall (2006) associates resilience with the ability of an organization to keep, or recover quickly to, a stable state, allowing it to continue operations during and after a major failure or in the presence of hurdles. Thus, resilience includes both the ability to avoid failures and losses, as well as the ability to respond effectively after these have occurred. In the context of this research, the authors define resilience as the ability of a network to recover from a safety incident through the process of learning from failures.

Resilience engineering is useful for high-risk systems such as construction projects, that involve high interdependency among participants and high levels of uncertainty and variability. Resilience metrics are defined in this study according to the European Network and Information Security Agency (ENISA, 2011). The categorization of these metrics uses a two-dimensional approach. The incident-based dimension divides resilience into three temporal phases: preparing for resilience "before" the event happens, delivering the service "during" the occurrence of an incident, and recovering to normal operation "after" the event.

Resilience is thus expressed over the three phases a system undergoes, which are tailored to match the scope of this research: (1) preparation phase (preparedness) includes all the measures implemented to help the system cope with risks and challenges and avoid their occurrence, (2) service delivery phase (incident occurrence) measures the system's operation once an incident occurs, its functionality, and its readiness to detect faults, and highlights the difference in system performance before and after the incident happens, and (3) recovery phase (recovery) relates to the state of the system after the incident has happened, shows how fast normal operations are restored, and includes possible mitigation measures for recovery.

To assess the performance of protective measures and preparedness of the system, the percentage of incidents out of the total number of events is measured. In addition, the severity and frequency of incidents in relation to the inherent level of risks involved in the corresponding tasks can reflect the ability of the system to cope with potential hazards. For instance, if the number of severe incidents exceeds a certain limit, then the system has very poor defensive strategies and is unsafe. Incidents can be classified as light or severe depending on their impact. The severity of an incident can be reflected through the resulting injuries, network of people affected, financial losses generated, psychological traumas, interruptions to work, etc. The impact of incidents on the system reflects its robustness and availability of mitigation measures that reduce damages.

In the context of SNA, studying network resilience shows how robust a network is when confronted with hazards. In construction, this implies studying how people interact with each other when risks or accidents prevail on a project and measuring the impact of changes occurring to the network. This reflects how the network responds to risks, how fast it recovers after a failure, and the damages (i.e., lost connections or weaker links) that result from a breakdown. Looking at network resilience helps in:

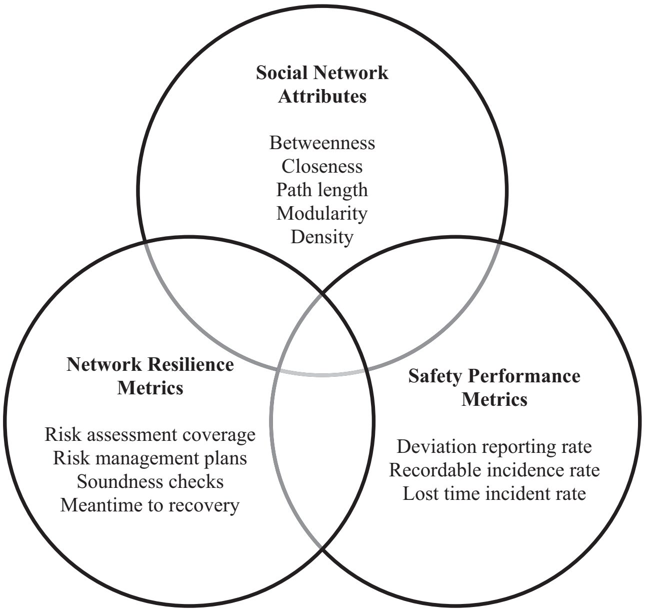

Fig. 1. Interrelationships between social network attributes, network resilience, and safety performance.

- *Reducing safety risks:* identifying important features in the network helps in setting up ways for reducing failure probability of the system (preparedness).
- *Mitigating failures:* analyzing important components of the network allows alleviating the consequences of safety risks through mitigation measures (incident occurrence).
- *Reducing time to recovery:* understanding the relationships in the network makes it possible to seek quick reactive measures after failure (recovery).

Risk management and safety performance are closely related since managing risks can reduce potential safety incidents. The need for managing safety is hence bound to the growing need for a comprehensive risk management process. In fact Rasmussen (1997), emphasizes the importance of managing risks in a dynamic society where drastic changes may affect work conditions. Rasmussen also points out the driving role of individuals in the propagation of an accidental course of events. Thus, modeling the system behavior by focusing on the network of people is essential to the risk management approach.

Risk management is perceived in this study as a controlling tool to maintain safe construction processes. The different stages in the risk management process are: risk identification, risk assessment/-analysis, and risk monitoring (Wehbe and Hamzeh, 2013). In this study, the network will be diagnosed to assess whether a risk management routine is employed or not. Each of the attributes will be addressed by understanding the social network of people in the system and ensuring that appropriate risk assessments and plans are done on each case study. Fig. 1 illustrates the interrelationships between social network attributes, network resilience, and safety performance.

3. Research methodology

3.1. Research objectives

The primary objective of the proposed study is to evaluate safety performance and relate it to network resilience through analyzing the social network of individuals with the goal of helping industry practitioners improve their safety management systems. Studying and analyzing the network will allow participants to enhance the design of their safety system. The specific aims of the research study are outlined:

(1) Understanding network characteristics by quantitatively analyzing the network where metrics such as density, average degree centrality, and closeness, are computed using Gephi as well as interpreting each of the metrics and correlating it to the network structure by examining communication patterns.
(2) Studying how communication among individuals impacts safety performance, which includes examining different visual features of the network and relating them to safety behaviors (e.g. clustering, shows the formation of groups associated with teams). The impact of communication will be detected to assess how it shapes safety responses to hazards. Moreover, collaboration and problematic areas will be spotted.
(3) Assessing network resilience and relating it to safety performance where the resilience of the network is checked to evaluate how robust it is, whether it can absorb safety risks and/or recover with the least damages. Resilience metrics are computed and compared for networks of selected case studies.
(4) Simulating the network behavior when reacting to a safety concern to understand patterns of reaction in relation to network structure and communication paths.

3.2. Research methodology

To achieve the research objectives, a methodology is developed as presented in Fig. 2. The methodology was performed on three on-going projects all executed by a well-known international contractor. The research procedure involves preparing and conducting a survey to collect data from participants on the different projects, then the collected data is refined and used to map the social networks using Gephi. Resilience metrics are then defined and calculated using the survey results and external data. Finally, the dynamics of safety interactions are simulated using NetLogo and correlation tests are performed on the resulting metrics to evaluate associations between SNA metrics, resilience metrics, and safety performance.

The communication study has been restricted to teams within the organization boundaries only. This choice is selected in order to standardize the process of data collection across the different case studies and have a common ground for comparison. External bodies, such as Police departments, municipalities, governmental regulatory parties, transportation departments, city/state HSE organizations, and others, play a role in studying the "incidence occurrence" phase. However, it is hard to reach these parties under each case and map their communication with the organization. They will also add more variability to the study and complicate the comparison process as there will be too many compounding factors. Due to these limitations, the study focuses on communication within the organizations to decrease variability and reflect the potential correlations between resilience, network structures, and safety performance. The implications of this restriction have desirable consequences such as a better replication and comparison across case studies, and less desirable ones such as a narrower capturing of the realistic system performance and a reduction in the generalizability of results to a broader environment that encompasses all these variables.

After administering the survey to the participants on each project, the data was collected and refined. Node and edge characteristics were entered into Gephi to map the network model reflecting safety interactions on each project where each network depicts the dynamics of safety communication and the relationships among individuals.

The graphs were then customized and the layouts adjusted to allow for proper visualization of data. The communities were then defined and the weights assigned to edges. Afterwards, quantitative analysis was performed and network metrics were retrieved from Gephi. The metrics and the structure of the network were interpreted to assess the interactions regarding safety in order to reflect on safety performance.

Next, the network resilience was measured by quantifying resilience metrics. These metrics were then compared against previous findings from SNA analysis. Finally, a NetLogo model was run to simulate each of the networks and inspect its behavior when a safety incident arises. SNA metrics were then correlated with network resilience on one hand, and with safety performance on the other. Also resilience metrics and safety performance were correlated. Results were discussed to compare the different projects and evaluate the safety system in place at the case company.

3.2.1. Survey design and administration

A survey was initially prepared and pilot tested to improve the quality of data to be collected. The survey targets parties involved in safety including crews, foremen, superintendents, field engineers, and managers. The response rate for the survey was 84% with 52 respondents for Project 1, 27 respondents for Project 2, and 43 respondents for Project 3. The goal of the survey is to understand how communication occurs within the organization to have a clear vision of how individuals interact on safety issues. As a Social Network Analysis survey, the main target is a proper visualization of social relations. Hence, the survey was designed with typical questions that address topics related to the list of contacts of each individual, the form and extent of contact, the nature of safety interaction, and the extent of safety interaction. It is used

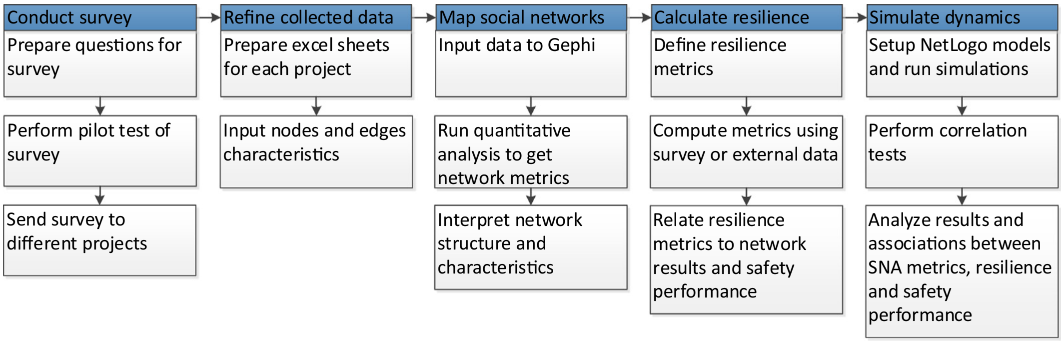

Fig. 2. Research methodology.

to gather information in order to map the social network of individuals involved in safety on the given projects at the case company. It addresses questions that help depict relationships among different individuals on the project and focuses on safety interaction and protocols. The survey was provided through an online portal and electronically shared with all participants on the selected projects.

The survey is structured into the following four sections:

- *Section 1:* asks to list the people with whom the respondent interacts (from within the organization) within the scope of his/her profession. For each person, a set of information is required regarding the mode of communication (e.g., face-to-face, emails, phone calls, meetings, green notes). The names of the people, including the person, are confidential and will not be disclosed in any private or public analyses, and will be given alphanumeric codes (i.e., Name = A1 or B9 ...) or titles (each designated by position and numbered) for the mapping of the social network.
- *Section 2:* targets the nature of safety interaction with the assigned individuals. Questions in this section aim to gather information on the purpose and frequency of safety communication (e.g., report safety issues, perform risk assessment, solve safety issues, send feedback on deviations, etc.).
- *Section 3:* investigates the extent of safety interaction in terms of frequency of safety communication and patters of such communications (daily, before a meeting, during a meeting, briefing before a job, safety training sessions, etc.).
- *Section 4:* addresses some safety processes held at the organization (risk assessment, soundness checks, behavior during safety accidents, etc.).

3.2.2. Case-study projects

For the purpose of the study, three projects from a contracting company were investigated. The company is one of the largest contracting companies in the Middle East and ranks among the top 25 international contractors with a revenue of $5.3 billion in 2013. It has offices and projects in over 40 countries, and a workforce of more than 130,000 employees handling a variety of projects ranging from building and civil engineering, heavy civil works, to pipelines and oil/gas projects. It is worth mentioning that the company has good records of safety on its projects and is keen on keeping safety at the top of its agenda. Future research might look at small-scale companies to compare them to large-scale ones and touch upon the core problem; however, shortage of data remains an essential problem when safety is discussed.

The scopes of the projects under study vary but are all interesting projects when it comes to studying safety. The first project aims at expanding the gas production of an existing plant and upgrading the gas gathering network in order to drill and tie-in additional new wells and install new compression stations to increase the gas production handling capacity. The value of the Engineering Procurement and Construction (EPC) contract is $203 million. The second project consists of a 265 km long dual four-lane expressway with an estimated cost of $2.6 billion. The expressway will provide strong new impetus to economic investment through building a logistics gateway to the Gulf region. The third project comprises engineering, procurement, construction, pre-commissioning, and commissioning of a sulfur station and pipelines. The contract value is around $555 million with a 40 months duration.

All three projects are large-scale projects and involve critical activities. Although Project 2 has the highest cost, it may be considered as having the lowest risk compared to Projects 1 and 3. The case studies selected are used to provide more compelling evidence and contribute to the robustness of the study. The cases are selected to address the questions of this research and the purpose of using multiple case studies is replication. Replication takes two forms: (1) literal replication, which takes place when two case studies produce close and comparable results and (2) theoretical replication, which occurs when results between two cases contrast under contrasting conditions (Hamzeh, 2009). The first and third project have the same type (oil and gas) whereas the second project is related to transportation with a different scope, which allows results to be replicated in both mentioned forms. The project selection process is based on the presence of safety systems, safety record keeping, accessibility to construction sites, comparability of projects, and permission to interview safety personnel. Moreover, all selected projects were at the construction stage with peak man-hours and thus involve many critical tasks requiring continuous safety monitoring.

This study analyzes and interprets inputs from practitioners and insights into the phenomenon under study. Using multiple sources of evidence when collecting and analyzing data is necessary to develop a process of triangulation of several congregating methods. Accordingly, this study employs the following types of triangulation (Meredith, 1998; Stuart et al., 2002; Yin, 2003):

- Data triangulation utilizing several sources (safety data, interviews, simulation).
- Theory triangulation (analyzing and comparing data across different projects and perspectives).
- Methodological triangulation (employing quantitative and qualitative methods).

4. Results

4.1. Social network analysis

In order to study the communication patterns related to safety on each project, Gephi was used to map the networks consisting of nodes and edges. Gephi is a visualization tool that enables the analysis of networks through metrics that the software automatically generates and reveals patterns in the structure of each communication network (Jacomy et al., 2009). The mode, form, and frequency (strength) of communication are attributes collected through the questionnaires supplied to the participants. Forms of communication cover aspects such as communicating to perform risk assessments, conduct safety checks, solve safety matters, send feedback on deviations, perform safety inspections, and discuss safety job planning. Moreover, the mode of communication, whether through meetings, face-to-face discussions, emails, deviation reports, or phone calls are indicated through the questionnaires. The frequency that reflects the strength of communication is also specified as a percentage range (rarely, 0–20%, 20–40%, etc.).

The characteristics of communication are reflected in the mapped communication structures in Gephi and reflected by having thinner or thicker connective links between the different nodes based on the data collected through the questionnaires. The graph type is selected to be "undirected" for all networks, considering two-way communication among all individuals. The clustering of groups is directly evident, as Figs. 3–5 show, reflecting the presence of communicating teams on site. Moreover, the diagrams show that management personnel have the biggest node sizes and represent influential individuals within each network. The ties within each team are stronger than those with separate teams; this is reflected in Gephi through having a higher weight for edges.

By observing the network of Project 1 depicted in Fig. 3, the network is centralized around the Health, Safety, and Environment (HSE) supervisor who has the highest degree value of 20 followed by the HSE manager. This can be associated with the fact that all safety communication and reporting on the project passes through

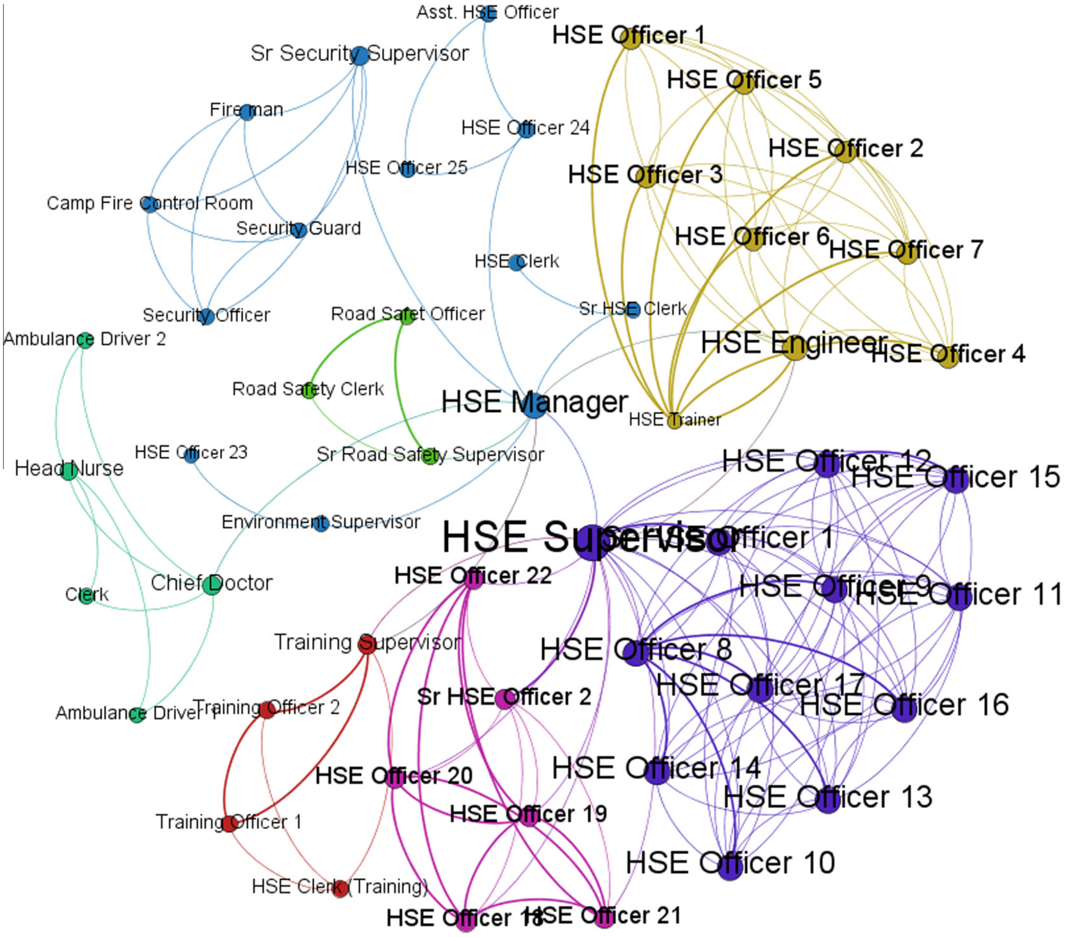

Fig. 3. Project 1 social network structure.

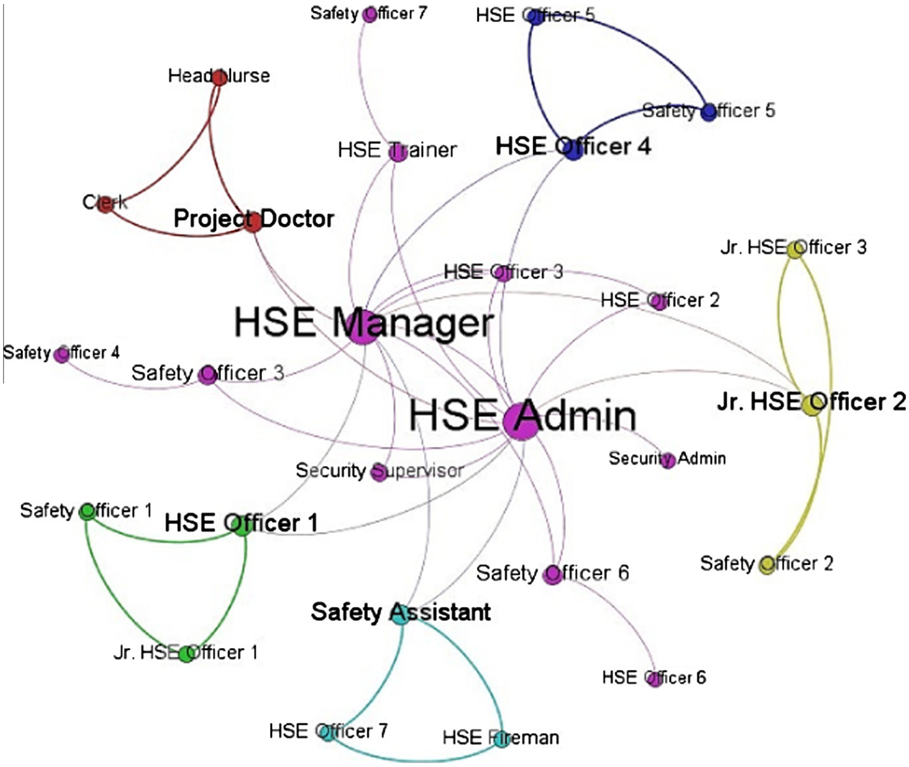

Fig. 4. Project 2 social network structure.

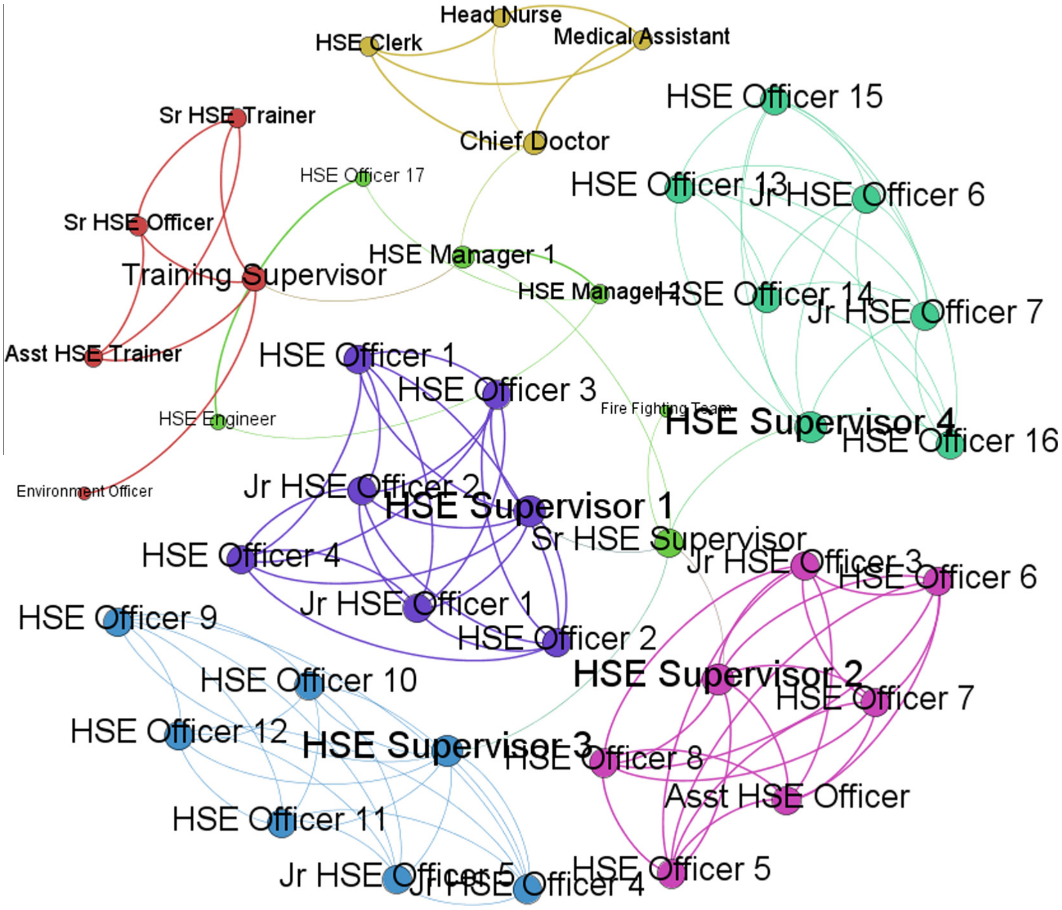

Fig. 5. Project 3 social network structure.

the HSE supervisor and as a result of organizational hierarchy. The different teams can be clearly visualized through denser ties among team members.

In fact, teams are assigned to different areas on site, and this is why little communication is noted between them. However, the HSE supervisor along with the HSE manager and HSE engineer play a brokerage role and bridge the communication between different parts of the network. This highlights their contribution in maintaining strong communication within the system, where they fulfill the gap among the teams.

Fig. 4 shows the Gephi network for Project 2. The number of players involved in safety is lower than that of Project 1, which is mainly related to the type of the project. Again the HSE manager has the biggest size node, along with the HSE admin. However, more nodes are observed at the periphery of the network with scarce communication. For instance, safety officers 6 and 7 are not easily reachable within the network which displays a high level of segregation.

Finally, Fig. 5 maps the network on Project 3 which has some resemblance to the network structure of Project 1. However, upon closer observation and after dividing the network as per modularity classes, two community structures (at the upper right and lower left) seem to have moderate communication between members. The edges connecting members have small thickness and hence indicate weak relationships among the team.

Upon mapping the different networks, a visual inspection helps gather information regarding the overall structure and drawing conclusions about the interaction between actors. However, social network analysis is carried out to give credibility to observations and evaluate the performance of each network against specific measures. Thus, quantitative social metrics are calculated for each of the project networks. Results were computed using Gephi and are summarized in Table 1.

The number of nodes in Table 1 indicates that Project 1 comprises the highest number of safety personnel (52) involved on site with the highest interaction indicated by the highest number of edges (165). Node metrics are averaged over the total number of nodes for each network. Average degree centrality represents the connectedness within a network and is highest for Project 1 with a value of 5.96. However, betweenness and closeness are higher for Project 3 with values of 54 and 3.57 respectively. It is important to note that a higher value of closeness indicates a more difficult communication path in the network where an individual is less reachable by others.

Table 1
Network metrics for the different projects.

Type	Metric	Project 1	Project 2	Project 3
Structure	Number of nodes	52	27	43
	Number of edges	165	42	109
Node (average)	Degree centrality	5.96	3.11	5.07
	Betweenness	50.48	22.15	54
	Closeness	2.98	2.7	3.57
Network	Density	0.124	0.12	0.121
	Avg. clustering Coefficient	0.851	0.695	0.878
	Average path length	2.98	2.704	3.571
	Modularity	0.692	0.671	0.769

Table 2
Resilience metrics corresponding to each phase (ENISA).

Phase	Resilience metrics
Preparedness	Risk assessment coverage Risk management implementation Soundness check for tasks
Incident occurrence	Deviation reporting rate Incident rate
Recovery	Meantime to recovery Network topology

Furthermore, the network density of Project 1 is the highest (0.124) and reveals a well-connected safety communication network. Project 1 has a lower modularity of 0.692, clustering coefficient of 0.851, and average path length of 2.98 when compared to Project 3 having respective values of 0.796, 0.878, 3.751. This denotes that the structure of Project 1 provides a relatively easier way to reach other individuals in the network as well as less groupings, i.e., more communication between different teams.

4.2. Resilience metrics

To further evaluate safety performance, resilience metrics corresponding to the three phases of preparedness, incident occurrence and recovery were developed in line with some of the metrics stated in ENISA, 2011. The metrics used in this study are listed in Table 2. The definition, objective, measurement method, frequency of measurement, and target values for each metric are presented in Table 3 to constitute a measurement framework for

Table 3
Resilience metrics definitions (ENISA).

Metric	Description	Objective	Measurement method	Frequency	Target values
Risk assessment coverage (RA)	Reports percentage of job operations that undergo risk assessment	Risk assessment reflects protective measures of the system and identifies level of risk on a project	Can be measured by dividing number of tasks subject to risk assessment by total number of tasks on a given project: $\text{RA}\ (\%) = \frac{\textit{Nbr of tasks with risk assessment}}{\textit{Total nbr of tasks on the project}} \times 100$	Ideally measured weekly for jobs assigned at the weekly work plan level	Should ideally be done on 100% of jobs presenting risks or potential safety issues. With no specified target value, critical tasks should still be assessed.
Risk management implementation (RM)	Reports percentage of job operations for which proper risk management plans were devised	Indicates that proper risk analysis is performed after evaluating risks. Mitigation can reduce consequences, eliminate/accept risks	Can be measured by dividing number of tasks with risk management plans by total number of tasks assessed for risk $\text{RM}\ (\%) = \frac{\textit{Nbr of tasks with risk mangt. plans}}{\textit{Total nbr of tasks with RA coverage}} \times 100$	Ideally measured weekly to track jobs for which risk assessment was done	Risk management should ideally be done on 100% of jobs that were diagnosed as risky or presenting potential risks
Soundness check for tasks (SC)	Reports percentage of job operations that were checked for soundness (prerequisites are available)	Checks task soundness to ensure safe operations. It indicates tasks checked for safety risks (hazard analysis) and complete criteria list	It can be measured by dividing number of tasks checked for soundness by total number of tasks assigned $\text{SC}\ (\%) = \frac{\textit{Nbr of tasks checked for soundness}}{\textit{Total nbr of tasks assigned}} \times 100$	Measured at look-ahead planning level (three to six weeks prior to the tasks assigned)	Should be done on 100% of tasks assigned, however some new tasks may emerge during week of execution
Deviation reporting rate (DRR)	Measures number of safety deviations that were reported in a given time period	Indicates number of detected deviations and reflects readiness of the system to overcome risks and faults in current operations	Measured by counting number of deviations recorded over a given period of time $\text{DRR} = \frac{\textit{Nbr of deviations reported}}{\textit{Time period}}$	Should be done daily during course of execution and aggregated to evaluate project performance	No target value is set; however, deviations reported should not exceed a certain threshold and be used to trigger alarms for safety
Incident rate (IR)	Measures no. of safety incidents that occurred in a given period	Indicates efficiency of the safety system. It shows level of risk threatening the system	Measured by counting number of safety incidents occurring over a given period of time: $\text{IR} = \frac{\textit{Nbr of safety incidents}}{\textit{Time period}}$	Should be monitored daily during execution and combined to evaluate performance	Ideally set to zero to eliminate incidents. It is crucial to track and prevent number of severe incidents presenting threat
Mean time to recovery (TTR)	It measures robustness of the safety system after incident occurrences	It shows ability of the system to recover after an incident happens. Recovery is effective when precaution measures have been input in the system	It is calculated by dividing time between incident occurrence and recovery over number of incidents $\text{TTR} = \frac{\sum(\textit{Incident recovery} - \textit{Incident occurrence})}{\textit{Number of incidents}}$ If incidents are categorized by lost time and non-lost time injuries, it is measured through adding all lost time from injuries over total number of injuries	It should be checked continuously, depending on frequency of incidents	No target value is set; it must be low. The faster the system recovers, the stronger it is against potential threats. A zero value indicates immediate ideal recovery
Network topology	It measures robustness of network against link and/or nodes failure	It is directly related to network topology. Link/node failures represent risks undermining network performance as it loses its bonds and robustness	Not calculated. Performance metrics are a function of node/link failures. Network topology is simulated where a number of nodes and/or links are removed. Performance impact of certain response parameters is recorded. Effects of failures are visualized. Network degradation and comparison of metrics reflect resilience		

Table 4
Resilience metrics.

Phase	Metric	Project 1	Project 2	Project 3
Preparedness	Risk assessment coverage (RA)	100%	75%	85%
	Risk management plans (RM)	75%	60%	75%
	Soundness checks (SC)	100%	100%	100%
Incident occurrence	Deviation reporting rate (DRR)	18.1	13.2	20.3
	Recordable incident rate (RIR)	0.03	0.04	0.07
Recovery	Mean time to recovery[a] (TTR)	0	0	0
	Network topology	NetLogo	NetLogo	NetLogo

[a] The company has no lost time injuries to date on the corresponding projects.

resilient networks. Resilience metrics for the three projects are calculated as per the method shown in Table 3 and then presented in Table 4.

The percentages corresponding to risk assessment were retrieved by averaging answers from the survey questions addressing risk assessment and soundness checks held at the projects under study. Incident rates and mean time to recovery were computed after analyzing safety statistics reports from the three projects.

The calculated resilience metrics (risk assessment coverage, risk management plans, soundness checks, deviation reporting rate, recordable incident rate, mean time to recovery, and network topology) reflect that all networks perform proper risk assessment for tasks before execution, and devise risk management plans for implementation. Individuals claim that all tasks are checked for soundness to make sure all prerequisites are available prior to execution. However, it is not possible for soundness checks to be complete while risk assessment values are lower than 100%. This indicates that participants were not aware of the right meaning of "soundness" checks. Project 3 scores highest on deviation reporting rate and incident rate with respective values of 20.3 and 0.07. On the other hand, Project 2 has a low incident rate of 0.04 although risk assessment and management plans are done less often. This can be related to the smaller number of deviations of 14.2 on this project. Project 1 exhibits more resilience than the other projects, with a relatively high deviation reporting rate of 18.1. Deviation reporting reflects two contradicting notions: a high DRR indicates that the network uses reporting to avoid future recurrence of the problem through a learning process, however it also means that deviations are taking place. It is then important to study whether the network is able to contain them and keep incident rate at a minimum. Therefore, a higher reporting rate does not necessarily reflect or assume an advantageous state unless improvement actions are performed to counteract these events and prevent their future occurrence. The simulation performed in NetLogo (Section 4.3.) assesses the ability of individuals and teams to counteract such events and become resilient toward future occurrences.

Going back to the three criteria defined previously for network resilience, each of the resilience metrics reflects the network readiness to safety risks:

- A high preparedness metric implies a reduced failure probability. Since the system is well prepared, a safety incident is less likely to induce critical failures.
- A low metric for incident occurrence indicates that the system is not highly affected by the incident and hence mitigation measures are effective.
- A low metric in the recovery phase denotes a reduced time to recovery and hence a more robust system.

4.3. NetLogo simulation model

Gephi allows the visualization of the networks but the static mapping of network structure is not suitable for assessing network resilience. After calculating the resilience metrics (risk assessment coverage, risk management plans, soundness checks, deviation reporting rate, recordable incident rate, mean time to recovery, and network topology) in the previous section, NetLogo, a dynamic agent-based simulation tool (Wilensky, 1999), was used to investigate the results through modeling the behavior of the different networks regarding safety communications. A recent study by Al Hattab and Hamzeh (2015) developed models (in reference to the "Virus on a Network" model) to study the diffusion of design errors on traditional and BIM-based networks for better design error management. These models are modified in this research to simulate different scenarios and predict the dynamics of the network to reach resilience. The aim is to measure the time it takes and percentage of individuals to become resilient when faced with a safety alert. A sample NetLogo model is depicted in Fig. 6.

The evaluation of network resilience is based on the concept of chronic unease. This aspect is defined in behavioral safety as a state of skepticism about safety risks, as opposed to a normalization of risks. In other words, chronic unease is the opposite of complacency and is crucial to achieve safety leadership (Lewis, 2014). Hence, an efficient safety system encourages this feature among individuals who should not be tolerant about safety observations, but rather enquire and be aware of safety risks.

The scenario simulated using NetLogo is based on measuring how tolerant individuals are to recurring safety observations. Starting with an unusual safety observation (i.e., potential error), individuals in the network do not always attempt to investigate but rather wait until the error spreads and recurs with a certain spread chance. It is only after repetitive observations that individuals seek to check for possible reasons and resolve the error. At different instances, individuals succeed in preventing an error from generating a safety incident at a certain recovery chance. The network hence develops resistance to future incidents and strengthens its resilience against safety risks. The parameters used in NetLogo for the simulation are detailed in Table 5.

For the sake of comparison between networks, the same parameters were held constant and the behavior of each network was monitored to test for resilience. The error spread chance was kept constant at 5% to account for random safety observations that do not involve any future incident or cause perturbations to the system.

The values of the parameters listed in Table 5 (initial-outbreak-size, error-check-frequency, error-spread-chance, recovery-chance, and gain-resistance-chance) were held constant to have a common ground for comparison and reduce variations across the three projects. The simulation aims at studying the way the network reacts to a problem and not the effect of parameters on the network. The difference between recovery and resistance is important in this context. Recovery indicates that the safety observation didn't lead to a more serious incident, however it can still reoccur in the future. On the other hand, resistance implies a shield that prevents that same problem from recurring.

After running the model for each of the networks under different scenarios, results were averaged and resilience was associated

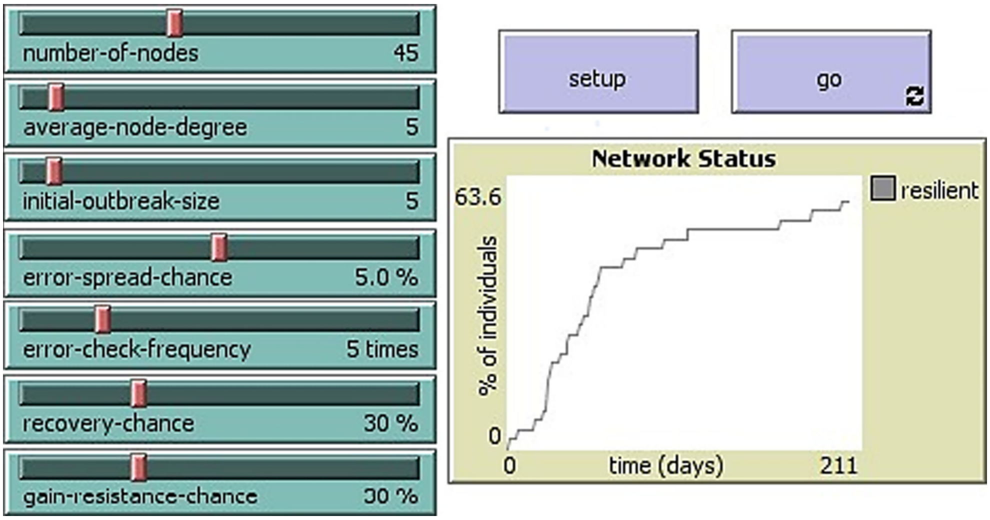
number-of-nodes 45
average-node-degree 5
initial-outbreak-size 5
error-spread-chance 5.0 %
error-check-frequency 5 times
recovery-chance 30 %
gain-resistance-chance 30 %

Fig. 6. NetLogo interface sample for Project 3.

Table 5
Parameters used in NetLogo.

Parameter	Definition	Values
Initial-outbreak-size	Number of individuals aware of safety observation	5
Error-check-frequency	Frequency of safety checks to investigate observation	5 times after recurrence
Error-spread-chance	Chance for safety observation to recur, i.e., a potential error	5%
Recovery-chance	Chance a person fixes error before resulting in an incident	30%
Gain-resistance-chance	Chance a person prevents future errors due to learning	30%

Table 6
Ratios for measuring resilience (NetLogo output).

Project	% of individuals	Time (days)	Ratio
Project 1 (nodes = 50, degree = 6)	62	130	0.24
Project 2 (nodes = 30, degree = 3)	46	80	0.17
Project 3 (nodes = 45, degree = 5)	58	200	0.13

with the ratio of resistant individuals in the network. This ratio was calculated through multiplying the percentage of resistant individuals by the total number of nodes in the network, and dividing it by the time required. The results are summarized in Table 6.

The results show that Project 1 has the highest ratio of individuals of 62% who gained resistance following a learning process that consists of a barrier that protects the network from potential errors that could diffuse later. These individuals acquired a sense of urgency when confronted with similar safety observations and hence learned to avoid their emergence into incidents.

In fact, at the first glance one might question the longer time it takes the network of Project 1 to become resilient. However, it is very important to account for the higher degree of the network. Although a high degree indicates better communication among individuals, it also denotes a faster spread of the problem. Having more connections causes the problem to spread to more people. However, the ability of the system and the time it takes it to develop resilience should be considered under two cases: (1) resilience develops faster when more safety discussions and prevention measures are implemented under collaborative environments, and (2) resilience develops slower when no efforts are performed to prevent the reoccurrence of incidents and when no safety precautions are considered or discussed. This doesn't imply that the network is weaker. Hence, computing the ratio accounts for the unequal sizes of the networks and provides a consistent way of evaluation. Therefore, Project 1 has a better performance than Project 2 irrespective of the decreased value in time. It is important to note that the higher the recovery and resistance chances are, the faster the error spreads and ceases. Resilience of a certain network increases with better connectedness and smoother communication flow.

5. Analysis and discussion

The networks of the projects reveal different characteristics pertaining to the nature of safety interaction among the team members. All networks show a relatively high modularity comprising dense connections within teams and weaker links across them. Moreover, the safety system in the case company is shown to be centralized on the upper management rather than being a shared responsibility. These results indicate the need for more collaborative projects that have more connections and frequent quality communications for a better safety culture. Higher betweenness and lower closeness on Project 1 bridge the gap between different entities on site and ensure proper communication flow as confirmed by Fig. 7 which maps the reporting mechanism and information flow within the network of Project 1.

Fig. 7 depicts the centralization of safety communication on three influential individuals in the network: the HSE manager, the HSE supervisor, and the HSE engineer. The communication flow goes up the hierarchy to reach the management level. Although reporting typically follows this procedure, it is a better practice to have two-way communications with managers and supervisors because they are more involved and provide feedback to workers at the job-front.

The type of project affects the type of safety network captured. For instance, Project 2 represents a transportation project and hence requires a different involvement in safety than oil and gas projects which involve more precarious tasks. This explains the

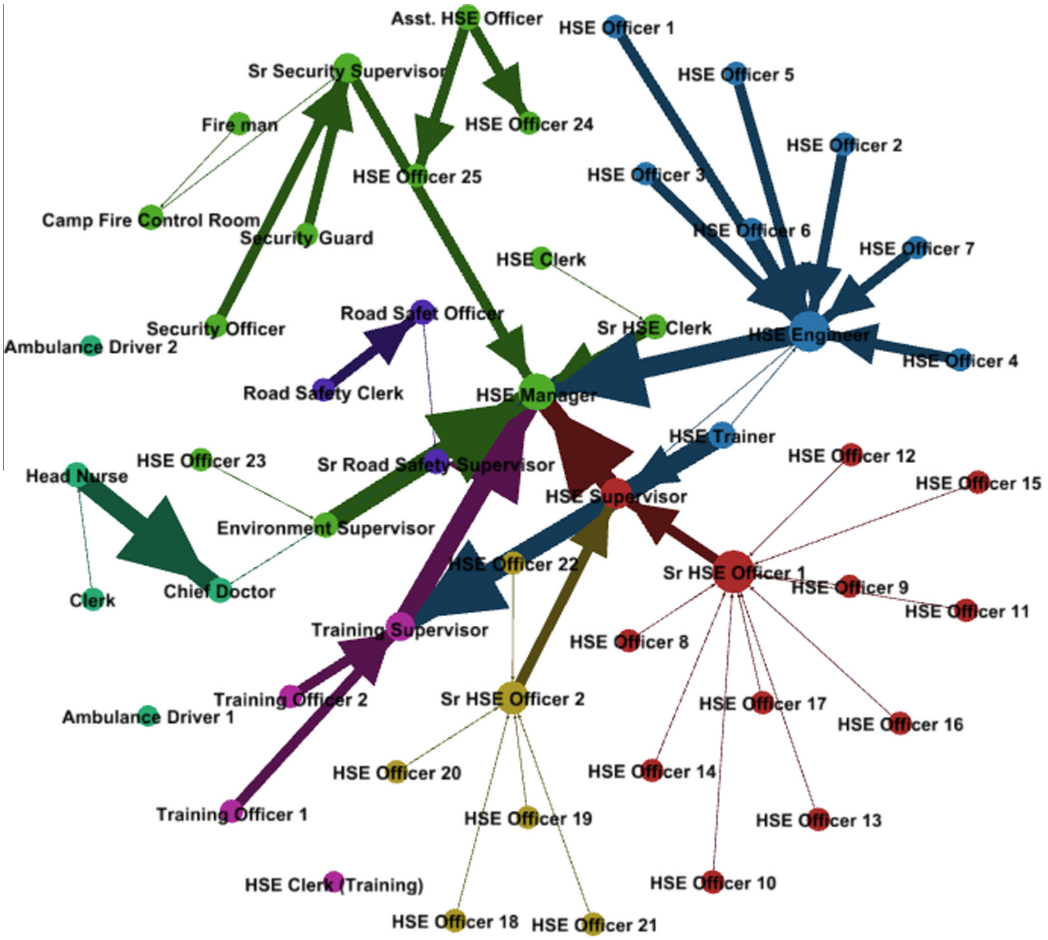

Fig. 7. Reporting and safety information flow on Project 1.

lower number of individuals and edges present in the network as well as the emergence of periphery nodes. Projects 1 and 3 consist of denser and more complex networks. However, the average node metrics for Project 3 show that higher closeness and average path length reflect a slightly more segregated network (than Project 1) conveying a lower level of communication than Project 1.

The resilience metrics calculated for all networks also confirm that a stronger communication structure ensures better safety management via robust bonds among individuals. Results show that the network of Project 1 is the most resilient network with the lowest incident rate and hence the best safety performance. A resilient network develops resistance to failures as it is shown to build up barriers and prevent recurrence of problems through a continuous learning process. Therefore, resilience is associated with a better safety performance as it allows the network to be more proactive and to anticipate potential system errors. Individuals within such a network sometimes develop chronic unease and become reluctant to tolerate deviations. However, these results do not give a global view of all projects and all cases, and they do not necessarily confirm that better resilience always translates into better safety performance. An alternative interpretation of this result might be that Project 3 contains more risky activities than Project 1. This can explain why the better resilience of Project 1 resulted in a better safety performance.

Questions in the survey targeted the exchange means as well as the extent of safety interaction for each of the networks. It is important to note that Project 1 with the best safety performance used face-to-face meetings as its primary means of communication, as opposed to Project 2 which focused more on emails and meetings. However, almost all projects had a high extent of safety communication including all venues (meetings, safety briefings before work commencement, training sessions, etc.).

In order to gather all data and carry out a comprehensive comparison of results, research findings are summarized in Table 7. The most important SNA metrics are used for comparison.

The main safety indices against which performance is measured on each project are: deviation reporting rate (DRR), recordable incident rate (RIR), and lost time incident rate (LTIR). These three metrics are measured based on actual data collected on the projects.

Results show that the SNA metrics calculated on each project may reflect their safety indices. For instance, low closeness and average path length values on Project 1 reveal a connected network that in reality has the lowest incident rate. Resilience metrics are also found to affect the safety performance of the network. When preparedness and resilience ratios increase, results of this study show that safety indices turn out to be better. For example, Project 1 has the lowest incident rate with 92% preparedness and 0.24 for the resilience ratio. For Projects 2 and 3, although preparedness is better on Project 3, the low resilience ratio has a bigger effect on safety performance. The incident rate on Project 3 is higher than that of Project 2, nevertheless, given that the two projects are of different nature, they cannot be directly comparable. An incident rate of 0.07 on an oil and gas project may represent a better measure than a rate of 0.04 on a transportation project given the greater risk associated with the oil and gas industry. The

Table 7
Summary of results.

	Metric	Project 1	Project 2	Project 3
SNA metrics	Betweenness	50.48	22.15	54
	Closeness	2.98	2.7	3.57
	Density	0.124	0.12	0.121
	Average path length	2.98	2.70	3.57
	Modularity	0.69	0.67	0.77
Resilience metrics	Preparedness	92%	78%	87%
	Resilience ratio (NetLogo)	0.24	0.17	0.13
Safety indices	Deviation reporting rate (DRR)	18.1	13.2	20.3
	Recordable incident rate (RIR)	0.03	0.04	0.07
	Lost time incident rate (LTIR)	0	0	0

Table 8
Correlation coefficients across SNA metrics and resilience and safety metrics.

SNA metrics	Resilience metrics		Safety indices	
	Preparedness	Resilience ratio	Deviation reporting rate	Recordable incident rate
Betweenness	0.90	0.06	0.98	0.37
Closeness	0.47	−0.54	0.91	0.85
Density	0.90	0.82	0.44	−0.50
Average path length	0.46	−0.54	0.91	0.85
Modularity	0.36	−0.63	0.86	0.90

correlation among the factors is not quite practical due to the limited values, which requires a larger set of data to be collected and further analyzed.

As for the safety indices used, deviation reporting has two different connotations. On one hand, a high DDR reflects that reporting of incidents is adequately carried out to benefit from the lessons learned and avoid their recurrence, i.e., develop resistance. On the other hand, once deviation reporting is increasing then deviations in the system are equally increasing. Project 1 has the lowest incident rate with a high DRR. This can denote that the network is more resilient and better at absorbing the errors before they generate incidents and unfavorable consequences. Moreover, the weight assigned to the recordable incident rate is greater than that of deviation reporting rate since RIR involves actual incidents whereas DRR only depicts potential incidents or simpler deviations to the safe working practices. This is why if a network has a higher incident rate even with lower deviations, it is still considered a weak network, while a network with a lower incident rate and higher deviations is a robust network that can contain problems and prevent them from developing into incidents.

Project 3 has a high DRR with a low incident rate value. The deviation reporting in this case could be interpreted as a better readiness to face future challenges for the network, along with the high value for preparedness. However, the resilience ratio is lower than that of Project 1 relating to the slightly higher incident rate shown on Project 3. In fact, the resilience ratio is observed to be the most consistent metric reflecting the performance of the network. As such, Project 1 can be given the best safety performance. However, this result can easily change if it was proven that Project 1 has significantly less inherent precarious tasks than project three. Although Project 2 is not in the same category as Project 1 because of its scope, it is interesting to compare different types of projects for better understanding.

5.1. Exploration and analysis of correlations between metrics

Correlation tests were performed to highlight potential associations between SNA metrics and resilience metrics on one hand, and between SNA metrics and safety metrics on the other. Moreover, correlations were tested between the results of resilience and safety metrics. Correlation results are listed in Tables 8 and 9.

Table 9
Correlation coefficients between resilience metrics and safety indices.

Resilience metrics	Safety indices	
	Deviation reporting rate	Recordable incident rate
Preparedness	0.79	−0.08
Resilience ratio	−0.15	−0.91

Results indicate that betweenness and preparedness are positively correlated with a value of 0.9. One explanation can be that a higher value of betweenness indicates that individuals with a "bridging role" connect more pairs of individuals, making it easier for individuals to reach each other with more communication paths being available. A higher level of betweenness can be related to a higher value of preparedness when all safety managers are properly communicating with team members in making sure that all risk assessment plans, hazard analysis, or sound checks are performed properly. This can then reflect the ability of the system to be better prepared to face risks and contain them. Similarly, betweenness and DRR are highly and positively correlated with a value of 0.98 implying that more communication among individuals and the presence of individuals with high influence on the network can be related to more reporting of safety observations. However, this result may be different on projects with a culture of blame which usually results in a lower DRR.

Relating these interpretations to actual events, Project 1 has an established schedule of regular HSE inspections on site. In November 2014 and during their regular site walkabout, the HSE team detected a gas leak of H_2S. To contain the risk and mitigate any potential consequences, the team followed a series of prevention measures. First, they restricted the entrance to the designated area and distributed respiratory devices to all nearby areas. External comers were also prohibited from entering the site and workers who previously accessed the contaminated area were examined. The HSE team rechecked all H_2S monitoring devices on site and performed a root cause analysis to reveal the reason behind the incident.

Closeness and DRR are positively correlated with a 0.91 coefficient value. Deviation reporting rate has dual meanings; a high value indicates a positive attitude toward reporting incidents and can help increase the readiness of the system, whereas, a high value reflects that more deviations are occurring and therefore the working practices are unsafe. In this regard, a high value of closeness indicates a longer path required by individuals to reach one another, which can be related to higher occurrences of safety deviations due to weaker communication and longer time for important safety-related messages to be transmitted. As a real life example, project uses Safety Observation Cards to keep track of all deviations occurring on site. One card details the case of a worker trying to warm up coverall using a heating torch. This act did not cause any minor burn or injury, however, it was flagged as an unsafe act. As a result, all supervisors held a toolbox talk the next day with their teams regarding burns and personal injuries. The safety team on the project encourages all personnel to actively engage in reporting any safety observation to constantly raise awareness at the workplace and avoid any potential incidents.

Density and preparedness are positively correlated with a 0.9 value. A higher value of density indicates a better connected network. This again favors the network in terms of preparedness against risks. A denser network involves individuals who will communicate and coordinate better whenever any safety incident occurs. Density and resilience ratio are also positively correlated with a 0.82 value. Similarly, a denser network with better preparedness can have a higher level of resilience. It can have a better ability to recover from failures and avoid potential similar events where the improved communication among individuals and the structure of the network makes it more robust. This correlation can be attributed to the importance of communication in establishing a safety culture. However, an alternative explanation may be that those projects that are having higher density are less complex which can translate in a higher levels of resilience and preparedness.

Average path length and resilience are negatively correlated with a value of −0.54. This result reflects a relationship between the increase in average path length value, which means harder communication paths and less reachability of individuals to others, and the decrease in network resilience since the safety robustness of the system can potentially decrease with weaker interaction in the network about safety related issues. Correlation results show that average path length and DRR are strongly and positively correlated at 0.91. One explanation for this result is that a higher average path length value can be related to more occurrences of deviations as looser network ties and long time required for transmission of safety-avoidance messages is related to an increase in deviations occurrence. Similarly, average path length is positively correlated with RIR at 0.85, where longer communication paths has a chance to be associated with a higher frequency of incident rates. This can be true when longer communication paths are slower and less responsive.

Modularity and resilience ratio are negatively correlated with a value of −0.63. One explanation is that when modularity increases, the network divides into isolated clusters and robust communication can be reduced. This can result in a reduction in the resilience of the system. If this is the case, the system does not act as one entity and hence its ability to avoid, mitigate, and recover from failures is reduced. These results indicate the need for more collaborative projects that have more connections and frequent quality communications for a better safety culture. A correlation coefficient of 0.9 between modularity and RIR indicates a relation between the increase in modularity and the increase of incidence occurrence where the absence of network unity may prevent the system from responding as one entity to avoid failures.

Results summarized in Table 9 show that preparedness and DRR are positively correlated at 0.79. A proper safety culture would invest the higher number of deviations reported to help the network adapt, include control measures and precautions to avoid failures, and establish ways to mitigate failures in case they occur. Since DRR reflects deviations and commonly potential incidents, the increased number of deviations alarms the network to react and be prepared; thus relating to the increase in preparedness.

Resilience ratio and RIR are negatively correlated at −0.91. Networks having a high resilience ratio can overcome risks and avoid their recurrence. This justifies the lower number of incidents observed. A higher resilience implies a better safety performance which is also associated with a denser network structure where individuals are tightly connected and interactive. An alternative explanation might be that those projects showed better safety performance are less complex and that is why they have lower RIR. However, the quality of timely interactions is very important for proper dissemination of safety information.

While all these interpretations between correlation coefficients are reasonable, more studies are required to confirm such results on other projects.

6. Conclusions and future research

Traditional safety management practices rely on the continuous monitoring of statistics and devising new schemes to attain goals while neglecting the building blocks of a safety system: the network of people. Embracing a good safety culture consists of developing the individuals while understanding the dynamics of interactions between them.

This research takes a different and novel approach by dealing with safety at the social level. By mapping the network on Gephi, safety performance on projects is assessed based on system resilience. Using social network theory, three projects were analyzed and compared through visualizing their structure and computing structure related metrics. NetLogo was also used to simulate the network model and check how it reacts to safety alerts. Results show that the network structure, communication patterns, and resilience shaped the safety performance on the project. A more cohesive network structure on a project implies better safety communication and more resilience toward safety risks. The stronger the network, the better its ability to respond to safety problems, recover effectively, and proactively engage in avoiding future occurrences. Better resilience is then directly associated with improved safety performance. The safety management system must be designed to allow for proper interaction among individuals who form a robust structure and ensure high performance.

Further research can be performed to investigate the behavioral aspects of a resilient network and determine which characteristics, apart from chronic unease, promote a better performing team on safety matters.

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