ANALYZING HAZARDOUS INTERACTIONS ON CONSTRUCTION JOBSITES USING SOCIAL NETWORK ANALYSIS

Kasim AlOmari[1], John Gambatese[2], Drew Gerkey[3], and Ahmed J. Al-Bayati[4]

[1] Assistant Professor, College of Engineering, University of Thi-Qar, Iraq; Email alomari.kasim@gmail.com.
[2] Professor, School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331; PH (541) 737–8913; Email john.gamabtese@oregonstate.edu.
[3] Asst. Professor, Anthropology, School of Language, Culture & Society, Oregon State University, USA; Email drew.gerkey@oregonstate.edu
[4] Assistant Professor, Kimmel School of Construction Management, 225 Belk, Western Carolina University, Cullowhee, NC 28723; PH (828) 227-2519; FAX (828) 227-7138; email: ajalbayati@wcu.edu

Abstract: In addition to its risky nature, the construction industry incorporates a social interaction aspect as one of its qualities. The study presented in this paper aims to investigate the interaction properties that impact safety issues on jobsites. To meet this objective, periodic observations of the work taking place on a building construction project were conducted. During the observations, tens of hours of video recordings of workers conducting their traditional jobs/tasks were taken. After the completion of the work, an analysis of the two-mode networks for the worker and design element interactions using the social network analysis method was conducted. Two design element cases were analyzed, the concrete slab and steel beam components of the structure. The analysis shows that the workers are highly connected when considering the worker-design element interaction. To some extent, this result confirms the impact of design elements on the risk level of a worker. In addition to investigating the risk results for different trades on the jobsite, this study is unique in that it is the first in construction safety research to develop and analyze two-mode networks on top of video observations. The construction community can benefit from this study by extending current knowledge of the interactions that might lead to indirect risks, and then planning the work in a way that prevents and/or controls these interactions.

1   INTRODUCTION

Everything in the life is part of a larger system or subsystem; these parts are connected and can be looked upon as networks of interactions. Without an understanding of the interactions among the components, there will not be sufficient "knowledge" to understand these systems. The analyst, observer, of any phenomenon that might represent a system decides the environment and limits of that system. For example, one might thing the construction project parts consisted of all the stakeholders, project equipment, processes, etc. while another might focus on some of these parts considering them a subsystem. Surely, the first approach is comprehensive in comparison with latter. Yet, research limitations might force researchers to focus on some parts of the system or the goal could be revealed in this limited focus. Different ways are available to study the interactions and network style of relationships, one of which is Social Network Analysis (SNA). SNA could be used to represent the parts, and their interactions, of a system. The main variables that are connected in this study network(s) include workers and design elements of a commercial building. The interactions assumed in the study are presented in a recently-

suggested model to explain a systemic view of accidents that happen on construction jobsite; the model is called Degrees of Connectivity (DoC).

DoC is an accident caution model that has been introduced by the authors in prior studies (Gambatese and Alomari 2016 and Alomari and Gambatese 2016). The concept is founded on the belief that there is a series of impacts of the project's design elements on workers and also among workers themselves. DoC focuses primarily on exposure and frequency. The DoC concept focuses on the interaction between workers, while also targeting worker interaction, both direct and indirect, with the design elements. Gambatese and AlOmari (2016) provide a more detailed description of the DoC concept and its development.

Accidents causation may be viewed from the perspective of connectivities and the DoC concept. Four types of connectivities between design elements and workers are envisioned within the DoC concept. In each case, the connectivity centers on a design element under consideration. The four types of connectivities are as follows (Gambatese and AlOmari 2016):
1. DoC #1: A worker is injured while working to construct the design element. The injured worker is in direct interface with the element under consideration during all phases of the element's construction.
2. DoC #2: A worker is injured while constructing other design elements that directly attach to or interface with the design element under consideration. The worker is interacting with the design element of focus in its final form.
3. DoC #3: A worker is injured while working to construct other design elements that are not directly attached to or interface with the design element under consideration. The worker may be constructing a design element that is nearby, but not attached to, the design element under consideration. The injured worker is directly exposed to the design element of focus in its final form.
4. Doc #4: A worker is injured as a result of other workers constructing, or interfacing with, the design element under consideration. The injured worker has no direct interaction with or exposure to the design element of focus in its final form. The connection of the injured worker to the design element exists through other workers.

Accidents still occur in workplaces which require more effort to determine their root causes. Indirect root causes of accidents are of concern as well and may require additional attention, which is the focus of this study. The objective of this study is to illustrate the basics of practical presence of the four DoC scenarios using SNA. Moreover, the study introduces the use of affiliation networks to the safety and health research community. It worth noting that in the discussion below, "W" refers to a worker, and "DE" refers to a design element.

2 LITERATURE REVIEW

2.1 Accident Models

The prevalence of injuries, fatalities, and safety issues on construction jobsites are commonly high relative to other industries, which is a reason for researchers to develop new models that explain and mitigate causes of accidents. Moreover, the high rates of injuries and fatalities also drive people to emphasize worker safety during the design phase (Karakhan and Gambatese, 2017 and Tymvios, 2017). DoC is a recent model initiated as part of the safety in design approach, and considers the impact of the design of an element on workers by emphasizing the interactions between design elements and workers. A systemic view of accident causation has been introduced to the research community in different studies (Jiang et al. 2014). While the present study is not considered a systemic study, it is consistent with systematic studies in that the main construction process variables, i.e., workers and work components, are considered and included.

2.2 Social Network Analysis

A network is a term that has diverse meanings depending on the discipline. For example, in social science, a network is defined as "a set of actors (or agents, or nodes, or points, or vertices) that may have relationships (or links, or edges, or ties) with one another" (Prell, 2012). Generally, social networks are used

to represent, detect, and quantify the correlations among different types of actors such as workers, projects, firms, building components, etc. In other words, a network and its players is understood by evaluating and grouping the players in the network using social network analysis tools.

An actor in an assumed network could be a human, organization, or anything else. The representation can be of a physical or nonphysical object. SNA provides the analyst with different measures, which are used to understand the characteristics of the network under consideration. Actors in a network might be of the same kind, such as workers only, which is called a one-mode network. Sometimes, the assumed relationships depend on the affiliation of actors in an event and the network is called an affiliation network.

An affiliation network is also referred to as a bipartite or two-mode network. In social settings, people attending a specific event and people living in the same block are examples of bipartite networks. In the present study, actors are the workers, the event that they are affiliated by is the construction component, and the type of ties is the impact of a component's design on the worker in terms of safety and health.

One important difference between one-mode and two-mode networks is the type of matrix used to create each type of network. An incidence matrix is used with a two-mode network while an adjacency matrix is used with a one-node network. An adjacency matrix should be a square matrix (n x n), while an incidence matrix may not be a square matrix (n x m) (Luke 2015). Even though, a bipartite network is important for representing relationships, and many real-life networks are of this type, it is not suitably appreciated in research and the dominant type used are one mode networks (Liu et al 2012).

2.3 Network Examples Used for Analysis

In the first example, a steel frame with focus on the beams has been chosen to represent the DoC1. In this case, the design element of focus is the steel beam and the workers are installing the steel beam. For DoC2, after the steel beams were installed, other workers were installing metal decking to the beams. For the DoC3 scenario, workers nearby who were erecting a temporary steel stairway were selected. Steel beam installation was almost completed during the video recording observation and there were three ironworkers who were finishing the welding process. The second crew observed was the sheet metal workers who were attaching the metal decking to the beams to make the floors walkable. There were four workers installing the metal decking, in addition to a fifth worker who was driving a mobile crane to deliver the sheets to the building levels where the other workers were located. Even though the mobile crane operator might not be part of the same crew, he was considered for the analysis as the DoC concept applied to him as well in this situation. The third crew consisted of four workers who were installing the temporary stairs. The stairs were not attached directly to the steel beams but the work was in the same vicinity.

The second case example is the concrete slab, representing DE1 of DoC1. Three carpenters working to construct the slab were captured in the recorded videos. A mechanical contracting crew, which included five crew members, worked to install mechanical features (DE2) to the slab. Lastly, a plumbing crew working on installing plumbing features (DE3) and consisted of three workers was included to represent DoC3.

2.4 Network Creation

It is important to decide what relationship links the network actors. In this study, the presence of nearby workers and the closeness of the workers to the mentioned design elements are considered as the base for the relationship. With the presence of the workers and at a closer distance, the risk is higher.

A matrix of n rows and m columns, referred to as $\mathbf{A}_{nm}$, is an example of a created undirected network. The script n represents the workers and m represents the design elements. As it is assumed above, the connection between the workers and design elements represents the risk that is realized from the presence/closeness of the worker in one of the first three DoC scenarios. This connection implies that the worker is present to work on a specific design element and close to that design element and/or close to other emphasized design elements. Moreover, in the matrix $\mathbf{A}$, $\mathbf{a}_{nm} = 1$, if worker n is present/close while, or after, constructing the design element m. Otherwise, in the absence of one of the two conditions (presence and closeness) or both, $\mathbf{a}_{nm} = 0$. Since the networks are generally small, one mode matrices are extracted from the two mode matrices. In addition, extraction was performed because it is of interest to

understand the safety impact on the workers, which is the basis for the assumed relationship between a worker and design element. From this perspective, the researchers decided to analyze worker projections from the affiliation networks while only visualizing the affiliation networks. Visualizing the entire affiliation networks still helps in understanding network relationships.

Worker projection, or design element projection, could be extracted by creating a matrix **X** such that: **X = AA′**, where the columns and rows in **X** are equal and **m = n** in this case. It should be noted that in larger networks, a sample might be drawn from the original data which creates new values for n and m. The process of creating the co-affiliation network simply involves considering each pair of workers in the affiliation network and counting where the workers are both connected by a design element, which is assigned a value of 1 if connected and 0 if not connected.

3   ANALYSIS AND DISCUSSION

Considering the above discussions and to simplify the analysis, the first three DoCs will be analyzed altogether for each case (concrete slab and steel beam). The first three DoCs may be analyzed in this way because they all follow the same style of having W-DE interactions, and also analyzing them individually as smaller networks may not result in meaningful results. The fourth DoC will be analyzed separately for each case since it consists of W-W interactions. All of the analyzed networks are one-mode networks.

The process of analyzing the data follows several steps. First, different visualizations of the developed networks are presented. Second, node level measures are calculated, which commonly consist of the centrality measures. Lastly, network cohesion is checked to evaluate the network subgroupings. Moreover, by evaluating the cohesive measures, the study assesses not just direct relationships but also indirect relationships which may be understood better using cohesive and subgrouping measures.

Visualization is one of the most effective ways in presenting data and comparing among different data structures. Figures 1 and 2 present the two-mode networks for DoCs 1, 2, and 3 for the concrete slab and steel frame (beam) design elements, respectively. The affiliation networks of the concrete slab DE are consistent in terms of the workers' connection to the DEs in that the DEs are connected to the workers more consistently. It is interesting to note in some of the network figures show that some workers are separated from each other if only a direct connection is considered (i.e., there is no direct connection between the workers). However, when including the design elements, those workers are connected indirectly by DEs. As a result, having more connected workers by different design elements could be realized as a magnifier of risky situations as is suggested by the DoC concept. This notion is also helpful for showing to those who plan safety into projects that, practically, workers are connected by the components that they construct. Communicating the connection between multiple workers might enhance the understanding of who/which/when/where relationships that helps in creating safer designs. Without having affiliation networks visualized, this type of connectivity might not be revealed.
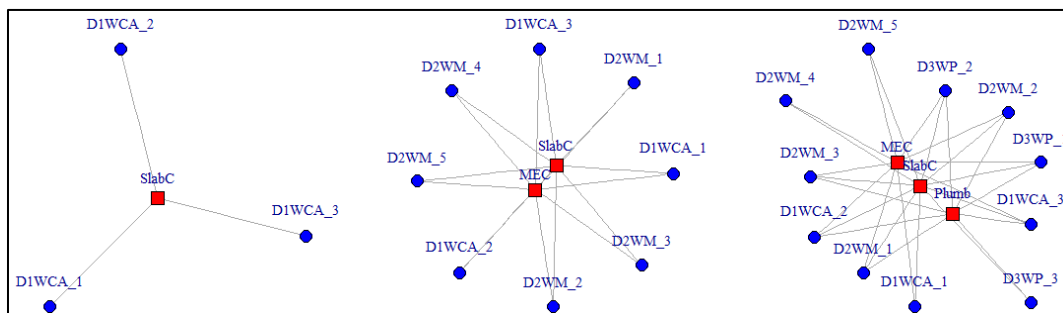

Figure 1: Concrete slab affiliation networks with DoC1 (left), DoC2 (middle), and DoC3 (right)

Other visualizations can be developed of the co-affiliation network for DoCs 1, 2, and 3, combined, and individually for DoC4, for both emphasized design elements. These networks are shown on Figures 3 and 4. Analysis of these networks is depending on the several common measures.
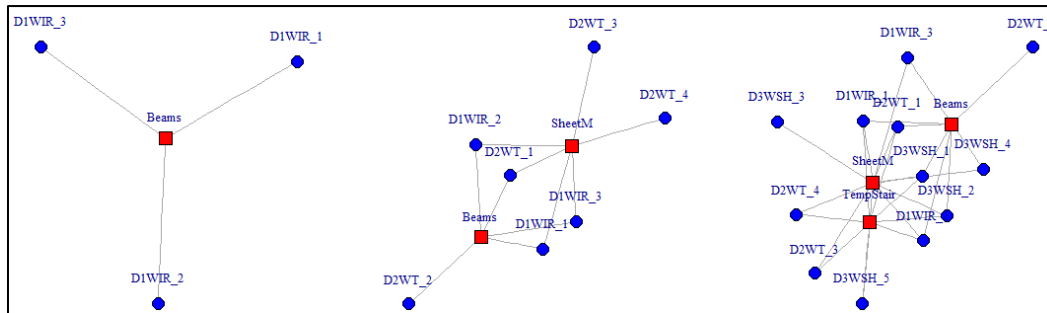

Figure 2: Steel beam affiliation networks with DoC1 (left), DoC2 (middle), and DoC3 (right) scenarios

Only workers who were captured in videos are considered for analysis even though a trade crew is large. In social studies having smaller networks might be interesting because this implies that the actors might have obvious connections. In construction, however, having larger networks is riskier since the connections take in mind the two mentioned conditions, presence and closeness.
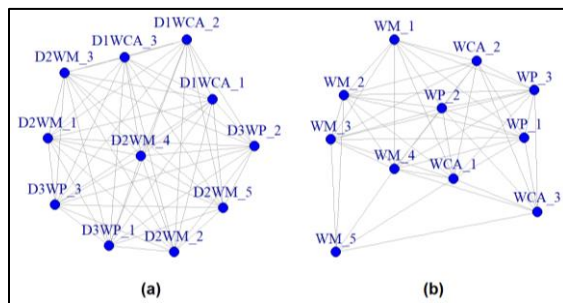

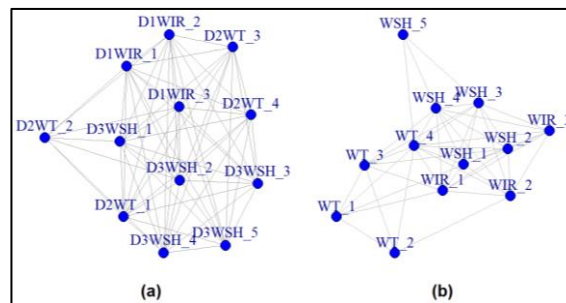Figure 3: Co-affiliation networks of concrete slab: (a) DoCs 1- 3 and (b) DoC4

Figure 4: Co-affiliation networks of steel beam: (a) DoCs 1 - 3 and (b) DoC4

Two approaches will be used to analyze the previous networks: on an individual level and a network level. The power that a single actor may have in a network is not immense on its own, but a result of its position within the network structure. In addition, since the position and dominance of a worker is important, it is of interest to calculate different centrality measures. Analyzing these kinds of measures would be more useful to evaluate patterns rather than single nodes (Luke 2015); therefore, this strategy will be adopted in the analysis. The prominence of a worker in a network is judged by having more workers connected to that worker, depending on presence/closeness relationship. Prominence of a worker is represented by the worker's centrality in a network. The simplest type of centrality is the degree centrality which refers to the edges that each node has, and is calculated using Equation:

$$C_D(n_i) = d(n_i)$$

As shown in Figures 3-a and 4-a, all of the workers are highly connected to each other. Centrality was considered only for networks that based on W-W interactions and the projections result from W-DE interaction networks. For the concrete slab DE, it is revealed that all workers have a degree centrality of 10, while for the steel beam DE all workers have degrees of centrality of 10 or 11, excluding WT_2 who has a degree centrality of 7. A degree centrality of 7 means that the lowest connected worker has seven edges. Figures 3-b and 4-b, which represent DoC4 for the concrete slab and steel beam, respectively, reveal that some workers have high degrees of centrality while others have lower degrees. The reason for the differences between Figures 3-a and 4-a on the one hand and Figures 3-b and 4-b on the other hand

is that the first figures are co-affiliation networks, which means that workers are connected in more than one way, i.e. during design elements.

Closeness is another useful measure for node prominence and is calculated as shown in equation below where *d* is the path distance between two nodes:

$$C_C(ni) = 1 / \sum_{j=1}^{g} d(ni, nj)$$

Prominence that results from closeness can be interpreted as meaning the node is more prominent if it is close to other nodes. The closeness values of the DoC3 scenarios for both DE cases are found to be higher than those of both DoC4 scenarios. This result can be justified by the closeness among workers resulting from connectivity of the workers with design elements in the DoC3 scenarios which is not the case in DoC4. All of the calculated values of closeness were in the range of 0.03 to 0.09. Most values are close to 0.09 which indicates that most nodes are close to other nodes which again confirms the idea of higher connectivity based on the DoCs concept. This closeness measure considered a support to DoCs presence because DoCs emphasizes the idea of connectivity. These centrality measures were considered because they both related directly to the DoCs understanding. That is, since DoCs focuses on the connectivity of W-W and W-DE and the degree centrality determines how many workers are connected to each other. In addition, closeness determines the shortest path between workers, with regard to this research problem, and the higher the number the closer the nodes are. Having workers close to each other assures another DoCs perspective as workers are close to each other creates a ground for higher connectivity.

After investigating the networks at the node level, another approach is to check the network using the cohesion property. One of the common measures of the level of cohesion of networks is the density. However, density may not be very useful in this kind of study because the ties represent the relationships between workers and design elements, and there are no ties among the workers themselves or the design elements themselves. The only networks for which the density reflects a useful measure are those developed for DoC4 for both the concrete slab and the steel beam DEs. Density for undirected network is calculated by the equation below, where *m* is the number of ties and *n* is the number of nodes:

$$D = 2m / \lfloor n(n-1) \rfloor$$

For DoC4 of both the concrete slab and steel beam DE networks, it was found that the density is 85% and 67%, respectively. Both density values are generally high, which supports the notion about networks beyond a single crew mentioned previously. That is, considering the relationships further than a single crew reveals that a network should be denser. Obviously, this result suggests that the, depending on the number of interactions provided, W-W interaction networks are risky because the workplace is crowded. Density is a measure of the whole network cohesion and not specified for evaluating subgroups, however, high density values refer to low or no subgroups, which will be assessed below. No subgroups indicate that all workers are affecting all workers, which may be realized as creating a high level of risk.

To investigate how connected are the work crews in the cases stated above, the RBGL package is used to check the clustering of the networks. Clustering coefficient is a measure shows the extent to which a node is clustered to other nodes in a network. It also be used to show how workers/crews are clustered to each other to reveal which worker/crew might impact other crews and which might require the designer to adjust the schedule/design to create a safer work environment on the jobsite. Excluding the network of DoC4 of the steel beam DE, the other three networks reveal that the members are highly connected and there are no subgroups. These characteristics are shown in Table 1.

Table 1: Clustering results of the concrete slab DE and steel beam DE

DE	Network	Cluster #	Worker Clusters		
Slab	DoC1-3	1	WCA_1 - 3	WM_1 - 5	WP_1 - 3
	DoC4	1	WCA_1 - 3	WM_1 - 5	WP_1 - 3
Beam	DoC1-3	1	WIR_1 - 3	WT_1 - 4	WSH_1 - 5
	DoC4	1	WSH_5	NA	NA
		2	WIR_1-3	WT_1-4	WSH_1-4

From an SNA analysis perspective, the actors in the groups are connected as one component. It can be interpreted that all of the workers are impacting each other in terms of connectivity that results from different DoC scenarios. That is, if there are different subgroups which are separated from each other, it might mean that one or both of the conditions (closeness and/or presence), is absent. Absence of one of the conditions might explain the riskiness of the situation while the analyzed networks show the opposite. In fact, the high connectivity can be seen in the figures above. In the DoC4 network, there are two clusters, one for all of the workers and the other for only the fifth worker in the sheet metal crew. The clusters make sense as it was mentioned that the fifth worker was a truck driver and was included because that worker was recorded in the videos as helping the sheet metal crew members.

4   CONCLUSIONS

This study is the first of the two steps in a study to investigate the practical presence of the recently developed DoC accident causation model. For first time in safety and health research in the construction industry, a two-mode, affiliation network was introduced to study the safety risk associated with design elements. The findings of the present study suggest that there is a basic indication of the presence of the DoC concept. This result was revealed from three analysis aspects: visualizations, node level evaluation, and network level evaluation.

The visualizations revealed that even though workers might not be connected directly by distance or present at the same time, they might be connected by the design elements that they construct. The node level analysis revealed that the workers have high values of degree centrality and low values of closeness. These values indicate the idea that the networks are connected very well at the worker level. Lastly, the network level and subgrouping analyses explained that workers working on the two selected cases, concrete slab and steel beam DEs, are highly connected. In addition, from a social network analysis perspective, there are no subgroups, which confirms that the actors in each network are impacting each other in terms of safety as a result of the connectivity concept.

The results of this study confirm to some extent that not only are the networks dense and connected, but our understanding of safety risk is extended further than the traditional way of thinking with construction worker safety. The analysis ultimately reveals that if there is an ability to change the design of an element, either its physical nature, through timing of its construction, or other means, the changes could help to produce a safer work environment. The safer work environment could be created by having less dense networks.

5   References

Alomari, K.; Gambatese, J. (2016). "Degrees of connectivity impact on construction worker safety." In Proceedings of the Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan, San Juan, Puerto Rico, 31 May–2 June 2016; pp. 2783-2792.

Chi, S., Han, S., and Kim, D.Y. (2013). "Relationship between Unsafe Working Conditions and Workers' Behavior and Impact of Working Conditions on Injury Severity in U.S. Construction Industry." J. Constr. Eng. Manage.139:826-838.

Choi, B., Ahn, S., Lee, S. (2016). "Role of Social Norms and Social Identifications in Safety Behavior of Construction Workers. I: Theoretical Model of Safety Behavior under Social Influence." J. Constr. Eng. Manage.

Gambatese, J.; Alomari, K. (2016). "Degrees of connectivity: Systems model for upstream risk assessment and mitigation." Accid. Anal. Prev. 2015, 93, 251–259

Jiang, Z., Fang, D., and Zhang, M. (2014). "Understanding the Causation of Construction Workers' Unsafe Behaviors Based on System Dynamics Modeling." Journal of Management in Engineering, ASCE, 04014099.

Karakhan, A. and Gambatese, J. (2017). "Safety Innovation and Integration in High-Performance Designs: Benefits, Motivations, and Obstacles." Practice Periodical on Structural Design and Construction. 22(4).

Liu, D., Blenn, N., and Mieghem, P. V. (2012). "Characterizing the Structure of Affiliation Networks" International Conference on Computational Science, ICCS 2012. Procedia Computer Science 9, 567 – 576.

Luke, D. (2015). A User's Guide to Network Analysis in R. Springer International Publishing Switzerland.

Prell, Ch. (2012). Social Netwrok Analysis: History, Theory and Methodology. SAGE Publications, London, UK. 1st Edition.

Tymvios, N. (2017). "Design Resources for Incorporating PtD." Practice Periodical on Structural Design and Construction. 22(4).