Dynamic Occupational Safety Risk Assessment in Construction Project using a Network-based Modelling and Analysis Framework

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Abstract

Occupational safety risk (OSR) assessment in construction projects is a complex process. Dynamic OSR assessment to assess OSR over time, according to the planned construction schedule, is uncommon because it is challenging to do despite its potential value to managers. This article proposes a new Dynamic OSR modelling framework, based on Network Theory. Its originality are (1) exploring the risk relationships among workers by combining construction activities done by different trades and the interactions among Safety Risk Factors (SRFs) causing safety accidents; (2) developing a dynamic risk network across construction stages for assessing construction workers' OSR prevention priorities dynamically. The application of the proposed approach is illustrated in the context of a tunnel construction project in China.

Introduction

In construction projects, specialised workers must collaborate to accomplish various activities via work cooperation and work communication (Pinto et al. 2011). With the construction industry still presenting high rates of Occupational Health and Safety-related injuries and fatalities, and the size and complexity of projects continuously increasing, the importance of managing health and safety risks increases, especially for projects occurring in a hazard environment, like tunnel construction, sea bridge construction or natural gas pipeline construction (Liu et al. 2018, Wang et al. 2021).

Regarding occupational safety risk (OSR), its dynamic assessment is challenging. Initially, the impact of a safety risk factor (SRF) to a safety loss depends not only on its own features, but also on the interrelationships with other SRFs in a construction system (Zhou et al. 2021). Different SRFs mutually affect, impede, and promote each other (Ren 1994). Additionally, trade workers perform a great diversity of construction activities causing various SRFs (Choe & Leite 2020). Thirdly, the worker who executes a task is directly exposed to its associated OSR, but is also indirectly exposed to risks produced by other workers e.g. involved in preceding or co-located activities(Andersen & Grytnes 2021). Finally, the interaction among SRFs or the relationship among workers is not constant, but changes dynamically with process convergence, construction schedule or other on-site requirements. All these observations mean that there exists great dynamicity in the OSRs throughout the project delivery, making their assessment very challenging.

Prior works on OSR assessment focus on two relatively independent scientific objects: engineering construction practice, or on the workers themselves (e.g. unsafe behaviours, safety attitude, safe climate) (Sousa et al. 2014). Few researchers have tried to assess OSR from the perspective of combing SRFs causing safety loss with the workers' construction activities (Grytnes et al. 2020). Existing research with OSR assessment mainly utilises Monte-Carlo Simulation (MCS), Analytic hierarchy process (AHP), Risk Matrix Method and Probability Method, cumulative prospect theory(CPT) etc. (Wang et al. 2021). Fuzzy Sets Theory (FST) has also been used to solve situations with incomplete or inaccurate data collection and non-quantified CRFs(Aghaei et al. 2022). As for the dynamic OSR assessment, it mainly focuses on technological development. For example, computer vision techniques have been considered to detect workers not wearing hard-hats or crossing hazardous areas. These approaches typically aim to provide information about for real-time OSR assessment, with models created according to the movement trajectory of workers on site causing immediate injury or the construction status causing sudden safety accidents (Alkaissy et al. 2020). As for cumulative assessment models of OSR, the researches are closely related to issues of bio-metrics, psycho-physiology and ergonomics. For example, Lombardi et al. (2011) designed a questionnaire for causes of falling, with the SRFs including worker demographics, injury, ladder and work equipment, environment characteristics, and work tasks.

However, if the construction worker with the highest OSR and corresponding construction activities can be predicted in advance, during construction planning, according to the established Construction Schedule (CS), then (1) targeted risk mitigation measures can also be planned; (2) OSRs and their evolution over time can be better communicated to the construction workers, which can be beneficial for their safety attitude (Liang et al. 2019). Therefore, it is important to find a practical method to predict OSRs dynamically as the project progresses through CS.

To address this problem, we propose to utilise the construction activity and construction environment as the links between SRFs causing safety loss, the workers, and the time dimension (through the CS). The risk transmissions among SRFs enables establishing risk chains. These relationships are identified through project document analysis (e.g. construction project plan, construction specifications, contracts for various professional projects, and the construction schedule). We then use Social Network Analysis (SNA) and Data Structure Analysis (DSA) to formalise the dynamic interactions among Construction Activities causing SRFs over time, identify the workers who are responsible for these CAs, and then establish a three dimensional dynamic occupational safety risk network (Dynamic-OSRN). A case study is presented to demonstrate the feasibility and effectiveness of the proposed method for OSR assessment over via Python, and visualised by Ucinet 6.0 and Net-draw.

Proposed Approach

Model Structure

To assess construction workers' OSR dynamically, this study designed an OSR assessment model using SNA and DSA. The method includes three steps: Risk Identification; Risk network establishment; and Risk analysis (See Figure 1).

Step 1 - Risk-related Factor Identification

In this study, understanding the external construction environment and internal construction activities is the basis to identify the SRFs, workers and occurrence of SRFs over time.

Step1.a - SRF Identification: First, the list of potential safety accidents is identified. Safety accidents are caused by the interaction of internal and external SRFs (Nasirzadeh et al. 2008). Therefore, given the specific safety accidents, related SRFs are identified from the external construction environment and internal construction activities. This identification work can be done through project document analysis, literature review, expert interview, or other relevant methods. Let's call $F = \{F_i, F_x \mid i, x \in [1,n]\}$ the SRF set.

Step1.b - Workers Identification: All construction activities are completed by specific types of workers, i.e. with specific skills. The relationships between workers and SRFs can be determined at the same time as the construction activities causing SRF are undertaken by the related workers. Besides, we assume there are several virtual workers who are related with the SRFs from the external environment since not actual workers can be held responsible for them. Let's call $P = \{P_j, P_y \mid j, y \in [1,m]\}$ the Workers set. The left-hand side of the diagram in Figure 2 shows the relationships between workers and SRFs.

Step1.c - Time Identification: The construction activities also enable us to link SRFs to time, since the timing of construction activities causing SRFs are presenting in the CS clearly. We also need to identify the evolution over time of SRFs linked to external construction environment through reconnaissance technologies, to match them with the established CS, like the monitoring or measurement technologies for detecting the Tunnel displacement, surface settlement, blasting vibration on tunnel projects. The CS normally presents the construction activities over continuous time periods (T) expressed in quarter, month, day, or other time periods as appropriate. Let's call $T = \{T_z, T_k \mid z, k \in [1,w]\}$, the Time set. The right-hand side of the diagram in Figure 2 shows the relationships between CS and SRFs.

Step 2 - Risk Network Establishment

Step2.a - Establishing a static SRF-Network: We proposed to utilise the risk chain theory to establish the static SRF-Network by qualitative analysis. Each safety accident is the result of several SRFs that are chronologically linked, and as such establish a transmission chain (Chen et al. 2019). Besides, SRFs can contribute to multiple risk events. As a result, these SRFs integrate multiple risk transmission chains, thus forming a SRF network. These pair-wise relationships between SRFs can be represented as 1-mode SRF adjacency matrix $A = [a_{ij}]_{n\times n}$ with:

$$a_{ix} = \begin{cases} 1, & \text{if}(F_i, F_x) \in \mathscr{A} \\ 0, & \text{if}(F_i, F_x) \notin \mathscr{A} \end{cases} \tag{1}$$

where $\mathscr{A}$={(F_i, F_x); if F_i is affected by F_x; $i, x \in [1,n]$} is the set of directional relationships between pairs of Fs. The middle of the diagram in Figure 2 shows of the relationships among SRFs.

Step2.b - Establishing a Dynamic-OSRN: *(1) Compute and modify 1-mode W-SRF adjacency matrix*
The 1-mode SRF adjacency matrix and the relationships between Workers and SRFs can further form the 1-mode W-SRF adjacency matrix $B = [b_{ij}]_{mn\times mn}$ with:

$$b_{ij,yx} = \begin{cases} 1, & \text{if } (P_jF_i, P_yF_x) \in \mathscr{B} \\ 0, & \text{if } (P_jF_i, P_yF_x) \notin \mathscr{B} \end{cases} \tag{2}$$

where (P_jF_i, P_xF_y) means a construction activity completed by P_j causing a SRF F_i is affected by the CA completed by P_x causing other SRF F_y. $\mathscr{B}$={(P_jF_i, P_xF_y); if a P_jF_i is affected by $P_xF_y; i, x \in [1,n]; j, y \in [1,m]$ and $P_jF_i \neq P_xF_y$} is the set of directional relationships between pairs of PFs. Note that when several workers are responsible for the a construction activity causing the focal SRF, their work affect each other when considering the risk allocation throng work corporation. Namely, if $P_i, P_j, \cdots, P_z$ do a construction activity causing the focal SRF F_x, we assume$((P_iF_x, P_jF_x, \cdots, P_zF_x) \in \beta$.The conversion above does not take it into account, so we corrected it.
(2) Compute and modify 1-mode W-SRF-T adjacency matrix
The 1-mode W-SRF-T adjacency matrix $C = [c_{jik}]_{mnw\times mnw}$ is built by using the 1-mode W-SRF adjacency matrix and the occurrence time of SRFs, with:

$$c_{jik,yxz} = \begin{cases} 1, & \text{if}(P_jF_iT_k, P_yF_xT_z) \in \mathscr{C} \\ 0, & \text{if}(P_jF_iT_k, P_yF_xT_z) \notin \mathscr{C} \end{cases} \tag{3}$$

where $(P_jF_iT_k, P_yF_xT_z)$ means a construction activity completed by P_j causing a SRF F_i during the period of T_k is affected by the construction activity completed by P_x causing other SRF F_y during the period of T_z. $\mathscr{C}$={$(P_jF_iT_k, P_yF_xT_z)$;

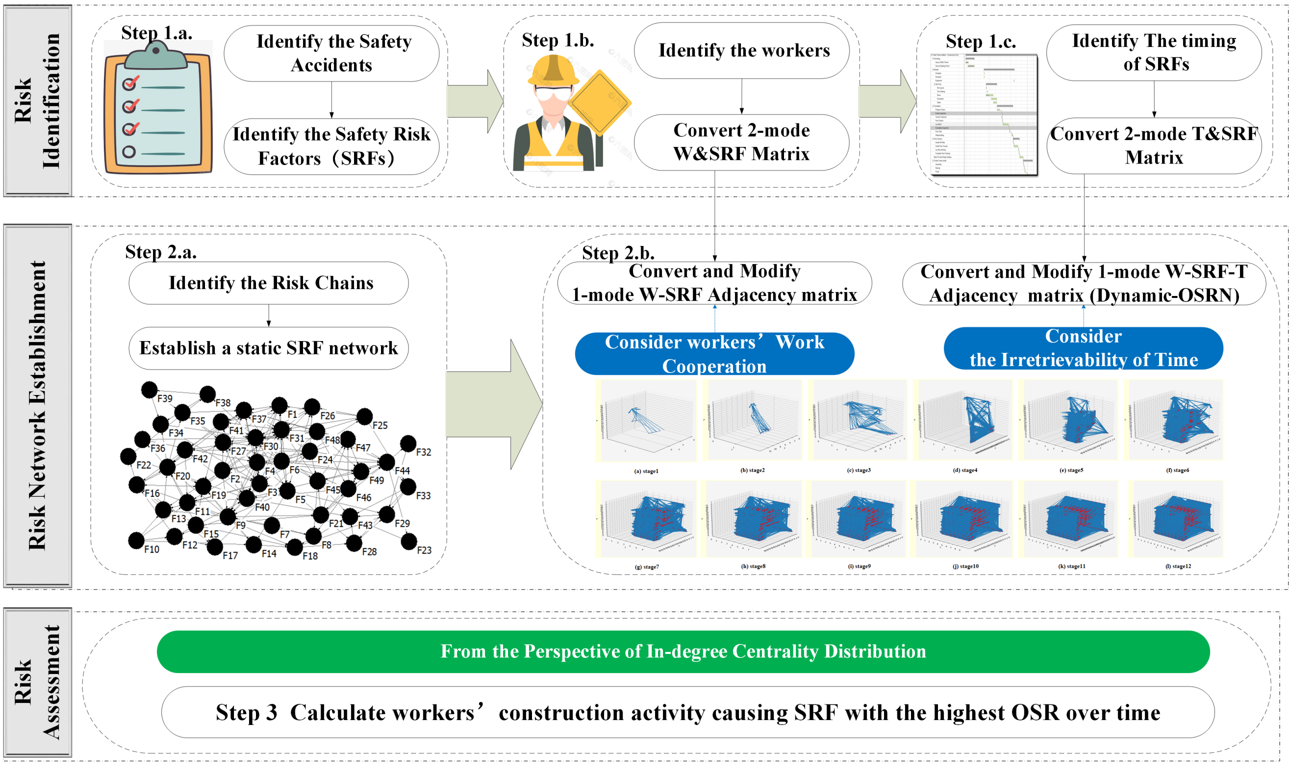
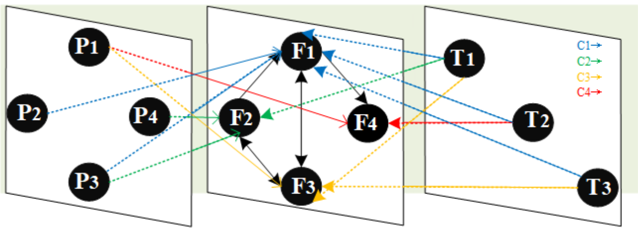


Figure 1: The Framework for occupational safety risk assessment model based on SNA-DSA



Construction Activity	SRFs	Workers	Construction Schedule	W-SRF	W-SRF-T
C1 →	F1	P2, P3	T1, T2, T3	P2F1, P3F1	P2F1T1, P3F1T1, P2F1T2, P3F1T2, P2F1T3, P3F1T3,
C2 →	F2	P3, P4	T1	P3F2, P4F2,	P3F2T1, P4F2T1,
C3 →	F3	P1	T1,T3	P1F3	P1F3T1,P1F3T3
C4→	F4	P1	T2	P1F4	P1F4T2

Note: 1) the node (W-SRF) in 1-mode W-SRF adjacency matrix means the worker (W) doing a construction activity causing a SRF;
2) the node (W-SRF-T) in 1-mode E-SRF-CS adjacency matrix means the worker (W) doing a construction activity causing a SRF during the period of T according to CS.

Figure 2: The schematic of the relationships between SRFs and workers, among SRFs and the occurrence time of SRFs.

if a $P_jF_iT_k$ is affected by $P_yF_xT_z; i,x = 1,2,\cdots,n; j,y = 1,2,\cdots,m; k,z = 1,2,\cdots,w$; and $P_jF_iT_k \neq P_yF_xT_z$ } is the set of directional relationships between pairs of PFTs.

Notes that SRFs caused by past construction activities should not be affected by SRFs caused by current construction activities. The model above does not account for this irreversibility of time and thus needs to be modified. Namely, if $P_jF_iT_k$ is affected by $P_yF_xT_z$ and $T_k < T_z$, then we should modify it to ensure that $(P_jF_iT_z, P_yF_xT_z) \notin \mathscr{C}$.

The set of W-SRF-Ts and their directional relationships captured in the dynamic-OSRN (see Figure3) can now be used for analysis.

Step 3 - Risk Analysis

We propose to utilise the in-degree centrality as a OSR index. In a network, the absolute in-degree centrality reflects the number of direct influence relationships between the focal node affected by other nodes (WE 2020). Consequently, in the Dynamic-OSRN, the absolute in-degree centrality of the focal node captures its level of influence from other nodes. The higher the in-degree centrality of a given W-SRF-T node, the higher level that this node is affected by other W-SRT-Ts, which means the higher level of OSR associated with that W-SRF-T.

For SRF F_i caused by the construction activity completed by P_j during the period of T_k, namely $(P_jF_iT_k)$, its in-degree centrality InD_{jik}, i.e. $OSRI_{jik}$, within time period T_k only, is calculated as:

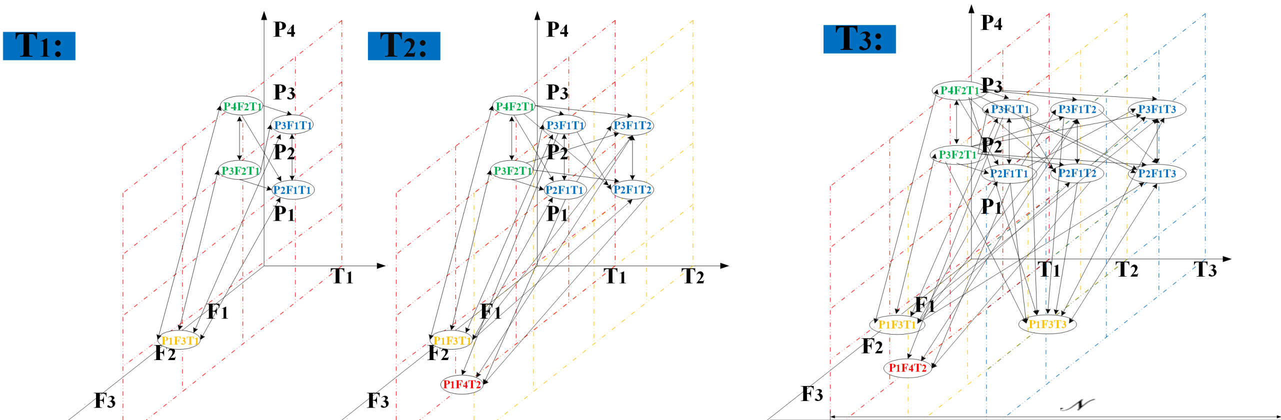
$$OSRI_{jik} = InD_{jik} = \sum_{j=1}^{m}\sum_{i=1}^{n} c_{jik,xyz} = \sum_{\mathscr{N}} c_{jik,xyz} \qquad (4)$$

where $\mathscr{N}$ means the number of nodes (i.e. W-SRF-Ts) in the Dynamic-OSRN.

Sometimes, a worker P_j may need to complete several construction activities causing different SRFs $(F_1, F_i, \cdots, F_n)$ during the period of T_k. Under this situation, for worker P_j in T_k, the worker's activity causing the critical SRF with the highest OSR-index is calculated as:

$$\max_i(OSRI_{jik}) = \max(InD_{j1k}, InD_{j2k}, \cdots, InD_{jnk}) \qquad (5)$$

i where n means the number of SRFs caused by the construction activities completed by the worker P_j on T_k. For



	P2F1T1	P3F1T1	P3F2T1	P4F2T1	P1F3T1
P2F1T1	0	1	0	0	1
P3F1T1	1	0	0	0	1
P3F2T1	1	1	0	1	1
P4F2T1	1	1	1	0	1
P1F3T1	1	1	1	1	0
OSR index	4	4	2	2	4

	P2F1T1	P2F1T2	P3F1T1	P3F1T2	P3F2T1	P4F2T1	P1F3T1	P1F4T2
P2F1T1	0	0	1	1	0	0	1	1
P2F1T2	0	0	0	1	0	0	0	1
P3F1T1	1	1	0	0	0	0	1	1
P3F1T2	0	1	0	0	0	0	0	1
P3F2T1	1	1	1	1	0	1	1	0
P4F2T1	1	1	1	1	1	0	1	0
P1F3T1	1	1	1	1	1	1	0	0
P1F4T2	0	0	0	0	0	0	0	0
OSR index		5		5				4

	P2F1T1	P2F1T2	P2F1T3	P3F1T1	P3F1T2	P3F1T3	P3F2T1	P4F2T1	P1F3T1	P1F3T3	P1F4T2
P2F1T1	0	0	0	1	1	1	0	0	1	1	1
P2F1T2	0	0	0	0	1	1	0	0	0	1	1
P2F1T3	0	0	0	0	0	1	0	0	0	1	0
P3F1T1	1	1	1	0	0	0	0	0	1	1	1
P3F1T2	0	1	1	0	0	0	0	0	0	1	1
P3F1T3	0	0	1	0	0	0	0	0	0	1	0
P3F2T1	1	1	1	1	1	1	0	1	1	1	0
P4F2T1	1	1	1	1	1	1	1	0	1	1	0
P1F3T1	1	1	1	1	1	1	1	1	0	0	0
P1F3T3	0	0	1	0	0	1	0	0	0	0	0
P1F4T2	0	0	0	0	0	0	0	0	0	0	0
OSR Index			7			7				8	

Figure 3: The directed graph of the Dynamic-OSRN and the risk index of W-SRF-Ts over time

example, taking the example in Figure 3), for P_3 on T_1, the worker's activity causing F_1 has the highest OSR, not the worker's activity causing F_2 since OSR-index of $P_3F_1T_1$ is 4, which is more than the one of $P_3F_2T_1$, at 2.

Case Study

Background of Case Study

The Yanmianqian tunnel, as the case project, is located in the Hunan province, China. The tunnel was completed in 2016. It took 18 months to complete with a traditional tunnelling technology. This case study can offer valuable references since its external environment, design and construction are typical in China, and even in other countries.

Risk Identification Results

Step1.a - Identification of SRFs: According to the official risk assessment report of Yanmianqian tunnel, the possible safety accidents include collapse, karst, water and mud gushing, mountain cracking deformation and surface subsidence. By manually analysing this official risk assessment report, 49 SRFs are identified, summarised in Table 1.

Step1.b - Identification of Workers: We further used document analysis to analyse the relationships between workers and SRFs for determining the workers set. The documents analysed include *the construction management plan of the Yanmianqian tunnel project, the special plan of geological prediction, the special plan of monitoring and measurement, and the guideline on safety for tunnel construction*. We identified 53 types of workers, that can be grouped into five categories, including: Senior managers, project personnel from the third parts, site managers, construction workers, and the virtual ones who are responsible for the external environment (see Figure4). The analysis also enabled us to form the relationships between 53 workers and 49 SRFs, summarised in Table 1.

Step1.c - Identification of Occurrence Time: According to the CS, the Yanmianqian tunnel was to be completed in 18 months, starting on October 1, 2014, and ending on March 30, 2016. We divided the construction period into 18 months, and the times of occurrence of SRFs are summarised in Table 1. Note that this project officially entered the construction phase in February 2015 (T_5), with the first 4 months being for planning. We consider it is meaningful to focus our assessment from T_5 since the construction workers construction workers on the site are engaged in the construction activities since stage T_5. they need to focus on their own OSR during the construction stage synchronously.

Network Establishment Results

The resulting Static-SRF network was established through the risk transmission chain analysis (See Figure 5).
The 1-mode W-SRF-T adjacency matrix is finally worked out using the approach described in Step 2b and the resulting Dynamic-OSRN is shown in Figure 6.

Risk Analysis results

We mainly focus on 14 kinds of construction workers whose construction activities cause SRFs that have the potential for direct physical harm (see green box in Figure 4).
The in-degree centrality distribution as the OSR-Index of a construction activity causing a SRF completed by workers at a specific stage has a non-negligible disparity across the project in the Dynamic-OSRN. For example, among all construction activities of P_{46} (Blaster) in T_5 , the CA causing F_{27} is most affected by other W-SRF-Ts, rather than the one causing F_{22} or F_{24}. The $P_{46}F_{22}T_5$, $P_{46}F_{24}T_5$ and

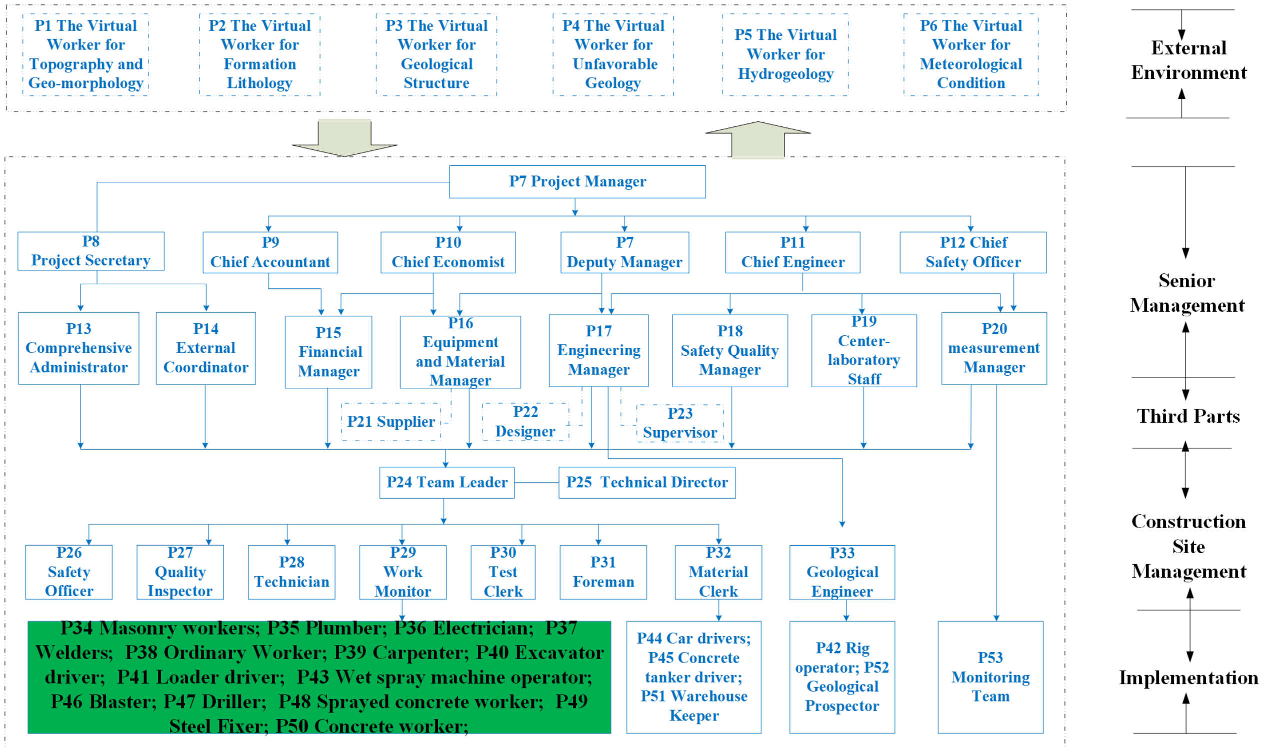
Table 1: The set of SRFs, the relationships between SRFs and workers, and the relationships between SRFs and CS

risk resources		SRFs	Workers	CS
External Construction Environment	Geology and Topography	F_1 Topography and Geo-morphology;	P_1	T_1 , T_3 , T_5 -T_{18}
		F_2 Formation Lithology;	P_2	T_1 , T_3 , T_5 -T_{18}
		F_3 Geological Structure;	P_3	T_1 , T_3 , T_5 -T_{18}
		F_4 Unfavourable Geology;	P_4	T_1 , T_3 , T_5 -T_{18}
		F_5 Hydro-geology;	P_5	T_1 , T_3 , T_5 -T_{18}
	Meteorological Condition	F_6 Meteorological Condition;	P_6	T_2 , T_4 , T_7 , T_8 , T_{15} , T_{16}
Internal Construction Activity	Geological Prosecution	F_7 Geological Information Collection and Check	P_{33}	T_1 , T_3 , T_6 -T_{18}
		F_8 Geological Prospecting in Practice;	P_{33} , P_{42} , P_{52}	T_1 , T_3 , T_6 -T_{18}
		F_9 Geological Prediction Report;	P_{33} , P_{52}	T_1 , T_3 , T_6 -T_{18}
	Tunnel Feature	F_{10} Information Collection of Design;	P_{22}	T_2
		F_{11} Burial Depth;	P_{22}	T_2
		F_{12} Size of Cross-section;	P_{22}	T_2
		F_{13} Slope;	P_{22}	T_2
		F_{14} Service Gallery;	P_{22}	T_2
	Construction Preparation	F_{15} Information Collection of Construction;	P_{11} , P_{14} , P_{17}	T_4 , T_{11}
		F_{16} Excavation Method;	P_{11} , P_{17}	T_4 , T_{12}
		F_{17} Blasting Method;	P_{11}	P_{17} T_4
		F_{18} Ventilation Measures;	P_{11} , P_{17}	T_4
		F_{19} Drainage Measures;	P_{11} , P_{17}	T_4
		F_{20} Support Design Method;	P_{11} , P_{17}	T_4
		F_{21} Practical Design of Construction Scheme	P_{11} , P_{16} , P_{17} , P_{18}	T_4 , T_{16}
	Excavation in Practice	F_{22} Excavation Speed or Excavation Footage	P_{38} , P_{40} , P_{46} , P_{47}	T_5 -T_{15}
		F_{23} Gas Pre-drainage Error;	P_{38}	T_5 -T_{13}
		F_{24} Blocking in Practice;	P_{46} , P_{47}	T_5 -T_{15}
		F_{25} Discard Slag Stacking;	P_{41}	T_5 -T_{15}
		F_{26} Groundwater Treatment;	P_{35} , P_{38}	T_5 -T_{15}
		F_{27} Other Excavation in Practice (Entering, Bottom Settling, Roofing);	P_{40} , P_{46} , P_{47} , P_{48} , P_{49}	T_5 -T_{15}
	Ventilation, Coal and Preventing Outburst	F_{28} Gas Pressure Relief and Emission;	P_{38}	T_7 -T_{18}
		F_{29} Ventilation in Practice	P_{27} , P_{28} , P_{36} , P_{37} , P_{38} , P_{49}	T_7 -T_{18}
	Waterproof and Drainage	F_{30} Grouting Water Plugging	P_{27} , P_{28} , P_{36} , P_{37} , P_{39} , P_{41} , P_{49} , P_{50}	T_7 -T_{18}
		F_{31} Drainage and Precipitation	P_{27} , P_{28} , P_{35} , P_{39} , P_{49} , P_{50}	T_7 -T_{18}
	Fire Source Control	F_{32} Electricity Operation in Practice;	P_{27} , P_{28} , P_{36} , P_{37} ,P_{49}	T_7 -T_{18}
		F_{33} Dust Cleaning in Practice;	P_{38}	T_7 -T_{18}
	Support and Lining in Practice	F_{34} the Quality of Initial Support Stiffness	P_{27} , P_{28} , P_{34} , P_{36} , P_{37} , P_{38} , P_{43} , P_{48} , P_{49} , P_{50}	T_5 -T_{15}
		F_{35} the Quality of Pre-Support;	P_{27} , P_{28} , P_{34} , P_{36} , P_{37} , P_{38} , P_{39} , P_{42} , P_{43} , P_{48} , P_{49} , P_{50}	T_6 -T_{17}
		F_{36} Effect of Pre-grouting;	P_{27} , P_{28} , P_{34} , P_{36} , P_{37} ,P_{41} , P_{43} , P_{48} ,P_{50}	T_6 -T_{17}
		F_{37} Reinforcement and Improvement of Formation;	P_{27} , P_{28} , P_{34} , P_{36} , P_{37} , P_{38} , P_{39} , P_{41} , P_{43} , P_{45} , P_{48} , P_{49} ,P_{50}	T_6 -T_{17}
		F_{38} Time of Construction of Initial Support;	P_{27} , P_{28}	T_6 -T_{17}
		F_{39} The Period of Closure Civilisation	P_{27} , P_{28}	T_6 -T_{17}
	Monitoring and Measurement	F_{40} Information of the Stability of Tunnel Face;	P_{19} , P_{20} , P_{30} , P_{53}	T_5 , T_{18}
		F_{41} Specification Requires Monitoring;	P_{20} , P_{33} , P_{53}	T_5 -T_{18}
		F_{42} Information of Water Volume,Quality, Pressure;	P_{20} , P_{33} , P_{52} , P_{53}	T_5 -T_{18}
		F_{43} Gas/dust (Concentration, Pressure);	P_{20} , P_{52} , P_{53}	T_5 -T_{18}
	Construction Management in Practice	F_{44} Safety, Emergency or Risk Management;	P_7 , P_{11} , P_{12} , P_{18} , P_{24} , P_{25} , P_{28} , P_{29}	T_4 , T_5 -T_{18}
		F_{45} Personnel Management;	P_7 , P_8 , P_{11} , P_{12} , P_{13} , P_{18} , P_{29} , P_{31}	T_4 , T_5 -T_{18}
		F_{46} Equipment Management;	P_{10} , P_{16} , P_{19} , P_{21} , P_{26} , P_{30} , P_{32} , P_{44} , P_{45} , P_{51}	T_4 , T_5 -T_{18}
		F_{47} Quality Control;	P_7 , P_{11} , P_{17} , P_{18} , P_{24} , P_{25} , P_{27} , P_{28} , P_{29}	T_4 , T_5 -T_{18}
		F_{48} Supervision	P_{23}	T_4 , T_5 -T_{18}
		F_{49} Schedule Management;	P_7 , P_8 , P_9 , P_{10} , P_{11} , P_{14} , P_{15} , P_{17} , P_{24} , P_{29}	T_4 , T_5 -T_{18}

$P_{46}F_{27}T_5$ are affected by 9,3 and 21 W-SRF-Ts respectively. Therefore, the maximum OSR-index for P_{46} on T_5 is the construction activity causing F_{27} (See table2).

Table 3 shows the maximum OSR-index of the construction activity causing SRF for each construction worker at different stages. Two phenomena are noteworthy for the period from T_5 to T_{18}.

For each stage, the CA with the maximum OSR-Index is



Note: (1) The job responsibilities of the project manager and the deputy project manager are similar, so their codes are both P7.

(2) The construction workers in the green box are OSR Assessment Objects

Figure 4: The set of workers

Table 2: The OSR index of the focal P_{46} -SRF-T_5 in The Dynamic-OSRN

P_{46} -SRF-T_5	the nodes which affect P_{46} -SRF-T_5	OSR Index
$P_{46}F_{22}T_5$	$P_{11}F_{16}T_4$, $P_{17}F_{16}T_4$, $P_{38}F_{22}T_5$, $P_{40}F_{22}T_5$, $P_{47}F_{22}T_5$, $P_{19}F_{40}T_5$, $P_{20}F_{40}T_5$, $P_{30}F_{40}T_5$, $P_{53}F_{40}T_5$	9
$P_{46}F_{24}T_5$	$P_{11}F_{17}T_4$, $P_{17}F_{17}T_4$, $P_{47}F_{24}T_5$	3
$P_{46}F_{27}T_5$	$P_2F_2T_1$, $P_2F_2T_3$, $P_2F_2T_5$, $P_3F_3T_1$, $P_3F_3T_3$, $P_3F_3T_5$, $P_4F_4T_1$, $P_4F_4T_3$, $P_4F_4T_5$, $P_{11}F_{16}T_4$,$P_{17}F_{16}T_4$, $P_{46}F_{24}T_5$, $P_{47}F_{24}T_5$, $P_{40}F_{27}T_5$,$P_{47}F_{27}T_5$, $P_{48}F_{27}T_5$, $P_{49}F_{27}T_5$, $P_{19}F_{40}T_5$, $P_{20}F_{40}T_5$, $P_{30}F_{40}T_5$, $P_{53}F_{40}T_5$	21

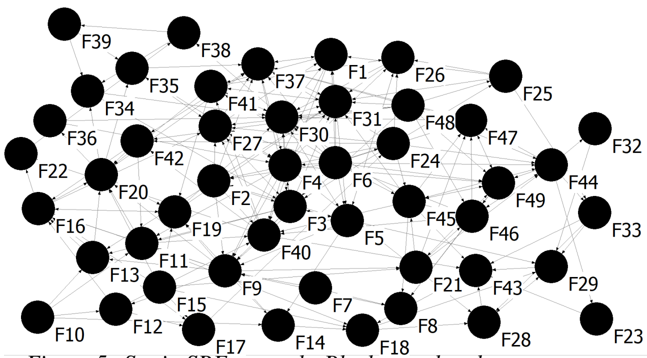


Figure 5: Static-SRF network. Black round nodes represent SRFs.

different for each kind of construction worker. For example, when entering the construction period (T_5), the construction activity causing F_{27} (Other Excavation in Practice (Wrong Excavation, Entering, Bottom Settling, Roofing)) is the highest OSR for P_{40} (Excavation Driver), P_{46} (Blaster), P_{47} (Driller), P_{48} (Sprayed Concrete Worker) and P_{49} (Steel Fixers). The $P_{40}F_{27}T_5$, $P_{46}F_{27}T_5$, $P_{47}F_{27}T_5$, $P_{48}F_{27}T_5$ and $P_{49}F_{27}T_5$ receive 21 other W-SRF-Ts influence.

While the construction activity causing F_{23} (Gas Pre-drainage Error) needs to be prioritised for P_{38} (Ordinary Worker). P_{34} (Plumber) should pay attention to the construction activity causing F_{26} (Groundwater treatment). P_{41} (loader driver) should focus on the one causing F_{25} (Discard Slag Stacking).

For each construction worker, they need to pay particular attention to the various construction activity causing the critical SRFs with the highest OSR at different stages. In other words, they need to pay particular attention to the construction activity causing the critical SRFs with the highest OSR over time dynamically. For example, P_{49} needs to complete several construction activities causing 8 SRFs, including F_{27} (Other Excavation in Practice), F_{29} (Ventilation in Practice), F_{30} (Grouting Water Plugging), F_{31} (Drainage and Precipitation), F_{32} (Electricity Operation in Practice), F_{34} (the quality of Initial Support Stiffness), F_{35} (the quality of pre-Support), and F_{37} Reinforcement and Improvement of Formation) (See Table 1). Table 3 clarifies that P_{49} should pay particular attention to F_{27} during T_5, F_{37} during T_6, and F_{30} during T_7.

It must be highlighted that the results have been reviewed by project management experts, including two project

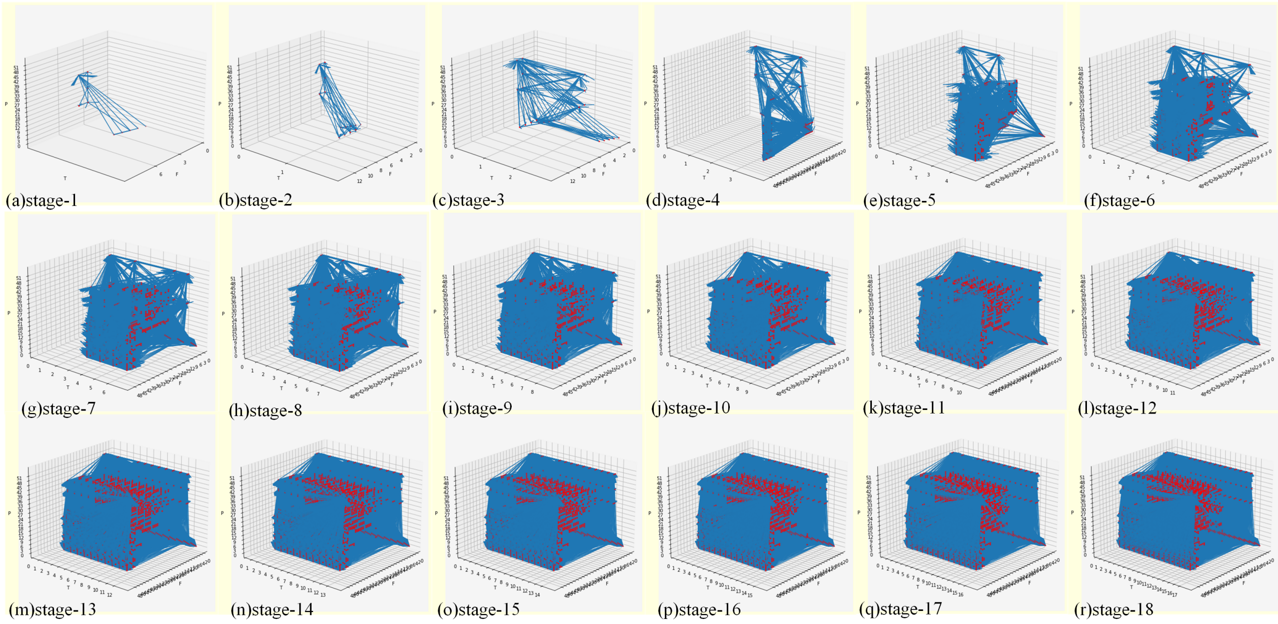


Figure 6: The OSR-index of construction workers in different stages

Table 3: The maximum OSR index of the focal W-SRF-Ts in The Dynamic-OSRN

Stage		P_{34}	P_{35}	P_{36}	P_{37}	P_{38}	P_{39}	P_{40}	P_{41}	P_{43}	P_{46}	P_{47}	P_{48}	P_{49}	P_{50}
T_5	SRF	-	F_{26}	-	-	F_{23}	-	F_{27}	F_{25}	-	F_{27}	F_{27}	F_{27}	F_{27}	-
	OSR Index	-	13	-	-	16	-	21	2	-	21	21	21	21	-
T_6	SRF	F_{37}	F_{26}	F_{37}	F_{37}	F_{37}	F_{37}	F_{27}	F_{37}	F_{37}	F_{27}	F_{27}	F_{37}	F_{37}	F_{37}
	OSR Index	87	22	87	87	87	87	46	87	87	46	46	87	87	87
T_7	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	134	106	145	145	134	145	71	145	134	71	71	134	145	145
T_8	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	181	149	196	196	181	196	96	196	181	96	96	181	196	196
T_9	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	228	192	247	247	228	247	121	247	228	121	121	228	247	247
T_{10}	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	275	235	298	298	275	298	146	298	275	146	146	275	298	298
T_{11}	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	322	278	349	349	322	349	171	349	322	171	171	322	349	349
T_{12}	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	369	321	400	400	369	400	198	400	369	198	198	369	400	400
T_{13}	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	416	364	451	451	416	451	223	451	416	223	223	416	451	451
T_{14}	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	463	407	502	502	463	502	248	502	463	248	248	463	502	502
T_{15}	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	F_{27}	F_{30}	F_{37}	F_{27}	F_{27}	F_{37}	F_{30}	F_{30}
	OSR Index	510	450	553	553	510	553	273	553	510	273	273	510	553	553
T_{16}	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	-	F_{30}	F_{37}	-	-	F_{37}	F_{30}	F_{30}
	OSR Index	550	490	602	602	550	602	-	602	550	-	-	550	602	602
T_{17}	SRF	F_{37}	F_{31}	F_{30}	F_{30}	F_{37}	F_{30}	-	F_{30}	F_{37}	-	-	F_{37}	F_{30}	F_{30}
	OSR Index	590	530	651	651	590	651	-	651	590	-	-	590	651	651
T_{18}	SRF	-	F_{31}	F_{30}	F_{30}	F_{29}	F_{30}	-	F_{30}	-	-	-	-	F_{30}	F_{30}
	OSR Index	-	557	681	681	162	681	-	681	-	-	-	-	681	681

managers of the Yanmianqian tunnel project, who reported that the main analysis is consistent with their experience. These contribute to validating the proposed method.

Discussion

The developed approach integrating SNA and DSA enables the project manager to evaluate construction workers OSR-index for determining occupational injury prevention priorities dynamically. This approach can be generalised and applied to any construction project. All SRFs, workers and the timing of SRFs are identified from official construction documents of the given construction project. The relationship among SRFs can be determined based on the construction process, working procedure connection or related standards and specifications. This method is clearer and more objective than many previous studies based on questionnaires and interviews (e.g. Lenzner et al. (2010)).

Another benefit of the proposed method is that it brings to light risk transmission chains, and that risk events linked to a given task are not just the result of improper behaviour of workers directly involved in that task, but by SRFs resulting transmitted from other activities, that often occurred long before that task.

Finally, this assessment model can help each worker accurately predict the OSR for their own construction activities and how it evolves at each stage. This should help them better judge and mitigate those OSRs.

Conclusions

Effectively understanding the risk transmissions among the construction activities causing various SRFs completed by different workers is a barrier to effective OSR assessment for project managers to adequately risk mitigation strategies. The framework proposed here establishes the relationships between workers and SRFs, the timing of SRFs, and the relationships among SRFs. A dynamic evaluation model based on the Dynamic-OSRN helps determine the construction activities completed by workers with the highest OSR-index over time (from the analysis of in-degree centrality distribution). The Yanmianqian project is used as an example to illustrate the work-ability of this proposed model. Directions for further studies include risk vector in the applications of risk transmission and risk relationships among construction workers.

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