Factors Influencing Safety Behavior of Workers in Human-robot Collaboration (HRC) Assembly Lines Based on ISM Theory

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Abstract. This paper investigates workers' safety behavior in human-robot collaborative (HRC) assembly lines, a key area in industrial engineering and operations management, especially with Industry 4.0's impact on interaction forms. By integrating the theory of planned behavior, an extended version applicable to HRC assembly lines is proposed. Using ISM based on 414 worker surveys, seven factors were identified, and matrices were established to define hierarchy and create a directional map. Results show that subjective norms positively influence safety behaviors and there is an interaction between perceptual behavioral control and situational awareness. These findings provide assembly line enterprises with a reference for workers' safety behavior, which can be used to reduce human errors and behavioral habit cultivation by enhancing the human-machine interaction model in order to reduce the occurrence of safety accidents and promote the efficient and collaborative development of the assembly line industry.

Keywords: Human-robot Collaboration (HRC) Assembly Line; Human-Computer Interaction; Theory of Planned Behavior; Recursive Structural Models

1 Introduction

Industry 4.0 has enabled human-robot collaborative assembly lines. Although HRC fatalities in China have decreased annually, unsafe operator behavior remains the cause of over 92.3% of engineering accidents (Figure 1). Human factors, such as self-awareness and emotions, are difficult to control and can lead to accidents directly or indirectly. This study employs a recursive structural model to analyze and categorize seven key factors influencing safe behavior, offering a significant reference for worker safety in human-robot collaboration.

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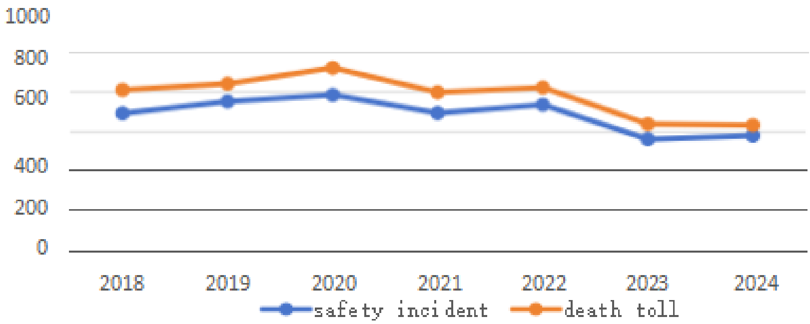
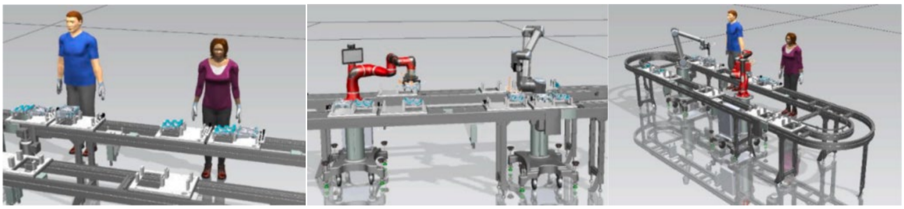


Fig. 1. Statistics on environmental safety accidents in HRC production in China from 2018 to 2024.

2 Human-robot collaboration (HRC) assembly line issues

Today's assembly lines depend largely on automation technologies such as industrial robots to enhance productivity via accuracy and repeatability. Yet, full automation is unfeasible for many manufacturers because of human workers' unique intelligence and skills.[1]. Thus, collaborative human-robot assembly is still the main production method, as human tasks offer flexibility and adaptability. Figure 2 shows the 3D layouts of an assembly line with (a) manual, (b) robotic, and (c) HRC environments. In line with Industry 5.0, assembly line design has progressed from manual to robotic and HRC settings, where robots collaborate with humans through advanced interaction and safety technologies. HRC integrates human and robot strengths to enhance productivity, flexibility, and adaptability.



(a) (b) (c)

Fig. 2. The 3D layout of an assembly line with (a) manual, (b) robotic, (c) HRC environment.

3 Classification of factors affecting human behavior

This study modifies and integrates the theory of planned behavior to create an extended version applicable to HRC assembly lines, considering the complexity of human-computer interaction, environmental characteristics, and worker activities.

①Behavioral attitudes. Behavioral attitudes reflect an individual's beliefs about the consequences of a behavior and their agreement with it.

②Subjective Norms. Subjective norms reflect perceived support from others in decision-making, and the Theory of Planned Behavior (TPB) shows a positive relationship between subjective norms and behavioral intentions.[2].

③Perceived behavioral control. This refers to a person's ability to manage opportunities and resources for an action and their assessment of its feasibility.

④Behavioral Intentions. Behavioral intentions, measured by indicators like attitudes, emotions, and motivations, influence behavioral decisions.

⑤Behavioral habits. Behavioral habits are stable patterns developed over time.

⑥Mind wandering. Mind wandering refers to the spontaneous shift of attention from the current task to internal thoughts, independent of external stimuli.

⑦Situational Awareness. Situational awareness is the ability to perceive, interpret, and anticipate environmental information for appropriate assessments and choices.

4 Data collection and reliability analysis

4.1 Scale development

The questionnaire in this paper focuses on seven factors, designed and developed through expert discussion and pre-survey revisions. It uses a five-level Likert scale, with the specific items shown in Table 1.

Table 1. Concept and scale composition

variant	encode	theme
Behavioral Attitude (ATT)	ATT1	I think it's a good decision to enforce safe behavior.
	ATT2	I think enforcing safe behaviors helps worker efficiency.
	ATT3	I think safer measures are good for workers' rights.
subjective norm (SN)	SN1	I will implement recognized security measures.
	SN2	Businesses advocate safety strongly, and I should implement safety measures.
	SN3	I'll perform a behavior because it's safer and well-received.
Perceived Behavioral Control (PBC)	PBC1	I have enough time to implement security measures.
	PBC2	I think I'm in control of what I do when I'm operating.
	PBC3	I believe I can change my behavioral habits that cause safety hazards.
behavioral intention (PI)	PI1	I want to enforce safe behavior.
	PI2	I am willing to combine considerations in order to implement safe behaviors.
	PI3	I am willing to recommend that a worker or coworker implement safer measures.
behavioral habits (BH)	BH1	I usually follow safety practices in my work.
	BH2	I would prioritize the safer way daily.
	BH3	I would follow safety protocols even when enforcing safety factors is less efficient than non-safety factors.
mind wandering (MW)	MW1	I know and understand the job parts prone to mind wandering.
	MW2	I know how to control my behavior to avoid the negative effects of mind wandering.
	MW3	Can I control my attention in a boring HRC assembly line job.
situational awareness (SA)	SA1	I can respond quickly to security incidents.
	SA2	I can effectively recognize impending security incidents.
	SA3	I can protect myself in the event of an accident by following the safety procedures for shutting down.

4.2 Data collection

This paper conducted a questionnaire survey of HRC assembly line workers with perceived safety competence from January to August 2024. Out of 435 collected questionnaires, 414 valid ones were analyzed (95.2% validity ratio). Data were gathered via field visits, online platforms, social media, and shift appraisals to ensure a diverse and representative sample. Respondents were informed of the survey's purpose and confidentiality, ensuring ethical legitimacy. Results show that 55.8% of respondents were female, 44.2% were male, with the majority aged 18–30 (249 respondents) and the fewest aged 60 or above (17 respondents). Specific data is shown in Table 2.

Table 2. Descriptive statistical analysis of demographic variables

variant	classification	frequency	Percentage/%
Gender	man	183	44.2
	woman	231	55.8
age	Under 18 years old	43	10.4
	18-30 years old	249	60.1
	31~40 years old	62	15.0
	41~60 years old	43	10.4
	60 years and over	17	4.1

4.3 Model credibility analysis

In empirical research, credibility reflects the stability, reliability, and consistency of measurement results. Systematic errors do not impact reliability[3]. This paper uses Cronbach's alpha to measure questionnaire reliability, and SPSS26 tests show that the alpha coefficients for each variable are above or close to 0.800 (in Table 3), indicating good reliability and passing the test.

Table 3. Reliability analysis

variant	encode	Cronbach's alpha
ATT	3	0.806
SN1	3	0.787
PBC	3	0.823
PI	3	0.846
BH	3	0.849
MW	3	0.825
SA	3	0.841

5 Interactive Structure Modeling

5.1 Overview of Interactive Structure Modeling

Interactive Structure Modeling (ISM) efficiently describes the interrelationships among elements in a structural system[4]. It visualizes complex relationships through matrices or hierarchical structures, clarifying the problem's hierarchy and entirety, and deepening the understanding of element connections.

5.2 Steps in Practical Methods for Interactive Structure Modeling

(1) Determine the set of elements (S) and the set of binary relations (R_b).

$$R_b = \{S_i, S_j | S_i, S_j \in S; S_i R S_j; i,j = 1,2,\dots,n\}$$

(2) Determination of relationship: the relationship use symbols V (row affects column), A (column affects row), and X (mutual interaction) to indicate relationships.

(3) Create the reachable matrix M: which is formulated as follows:

$$M = (A + I)^r$$

$$\boldsymbol{m}_{ij} = \begin{cases} \mathbf{1}, & \boldsymbol{S}_i \boldsymbol{R}' \boldsymbol{S}_j \text{ or } (\boldsymbol{S}_i, \boldsymbol{S}_j) \in \boldsymbol{Rb} \\ \mathbf{0}, & \boldsymbol{S}_i \boldsymbol{R}' \boldsymbol{S}_j \text{ or } (\boldsymbol{S}_i, \boldsymbol{S}_j) \in \boldsymbol{Rb} \end{cases}$$

(4) Reducing the strong connection relation yields M′.

(5) Hierarchical processing: Arrange rows and columns of M′ by descending count of element 1 in matrix M″.

(6) Draw a multilevel directed graph.

6 Interactive Structure Modeling building and analysis

The binary relationships of the seven influences were evaluated by industry experts based on the extended theory of planned behavior for HRC assembly lines and existing behavioral studies. and the results were as follows: S_1 directly influences S_4 and S_6, S_2 directly influences S_1 and S_4, S_3 and S_7 interact with each other, and S_5 directly influences S_4, and S_6 directly influences S_7.

6.1 Practical Method

(1) Determine the set of elements (S) and the set of binary relations (R_b)

Set of elements: S={$S_1, S_2, S_3, S_4, S_5, S_6, S_7$}

Set of binary relations: R_b={(S_1,S_4), (S_1,S_6), (S_2,S_1), (S_2,S_4), (S_3,S_7), (S_5,S_4), (S_6,S_7), (S_7,S_3)}

(2) Determine the relationship and plot it as a box plot

The supplementary recursive binary relation is as follows:

(V)	V		V	(V)	A	S_1
(V)	(V)		V	(V)	S_2	
(X)	(A)			S_3		
		A	S_4			
		S_5				
V	S_6					
S_7						

(3) The reachability matrix M

The reachable matrix M is obtained by adding the unit matrix to the boxplot:

$$M = \begin{array}{c} \\ S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ S_7 \end{array} \begin{array}{c} \begin{array}{ccccccc} S_1 & S_2 & S_3 & S_4 & S_5 & S_6 & S_7 \end{array} \\ \begin{pmatrix} 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array}$$

(4) Reducing the strong connectivity relation yields M′

$$M' = \begin{array}{c} \\ S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{array} \begin{array}{c} \begin{array}{cccccc} S_1 & S_2 & S_3 & S_4 & S_5 & S_6 \end{array} \\ \begin{pmatrix} 1 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{pmatrix} \end{array}$$

(5) Hierarchical treatment

Framing the decomposition of the largest order according to the number of elements 1 in each row of M' in descending order gives M''

$$M'' = \begin{array}{c} \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ S_1 \\ S_2 \end{array} \begin{array}{c} \begin{array}{cccccc} S_3 & S_4 & S_5 & S_6 & S_1 & S_2 \end{array} \\ \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 \end{pmatrix} \end{array}$$

(6) Plotting multistage recursive directed graphs: The relationship is shown in Figure 3

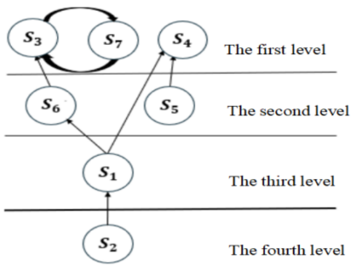


Fig. 3. Practical Methods Directed Graphs

7 Conclusion

This paper expands the theory of planned behavior for HRC assembly lines, analyzing the impact of seven factors on worker safety behavior through a survey of 414 workers. Using ISM, these factors are divided into four levels to explore their binary relationships and identify root causes of accidents and potential risks. The findings offer strategic recommendations for reducing perceived risk and improving human-machine collaboration in assembly lines. Future research should explore additional factors influencing the intention-behavior gap to advance Industry 5.0[5].

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