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Validating Measurement Structure of Checklist for Evaluating Ergonomics Risks in Heavy Mobile Machinery Cabs

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Abstract: Heavy mobile machinery cabs and their equipment are still not well adjusted to operators, so it is not surprising that we are still witnessing huge consequences of accidents at sites where they operate. The checklist with 39 questions, based on the previous research, is formed, and its' measurement structure has been tested on the sample of 102 transport, construction, and mining machines, including cranes, excavators, bucket wheel excavators, bulldozers, loaders, graders, backhoe loaders, trenchers, dump trucks, and scrapers by correlation analysis, Cronbach's alpha, Spearman-Brown and Kendall's W coefficient, exploratory factor analysis, and confirmatory factor analysis. The results validate the measurement structure of a checklist with only 17 items and five constructs. The results show that special attention should be put to the design of armrests and working conditions/exhaust gases, which are negatively correlated to cab interior space and task visibility. All other correlations between seat characteristics, the characteristics of armrests, whole-body vibration influences, reaching commands, the characteristics of cab interior space and environments, and interpersonal relationships are positive, which means that improvements to one area lead to improvements in another. Accordingly, the proposed model should be used for the fast, efficient, and cost-effective evaluation of ergonomics risks and as a guideline for further cab design improvements.

Keywords: risk management; ergonomics; heavy mobile machinery; cabs' design

MSC: 62H20; 62H25; 62H99

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1. Introduction

Safety, health, and risk management standards have been intensively improved for decades, which certainly leads to certain improvements in accident prevention [1]. However, the number of accidents, injuries at work, and fatalities is still not negligible and industrial safety should be at a higher level, especially in the transport, construction, and mining sectors [2]. The operation of heavy mobile machinery is still followed by numerous accidents with serious consequences, such as the deaths of employees, injuries, material damage, etc. [1,3,4]. The most probable reason for high accident rates is the fact that human factors and ergonomics issues, together with possible risk mitigation techniques, are usually neglected [2,5,6].

Previous research has reported numerous ergonomic inconveniences in heavy mobile machinery cabs. There often exist numerous operators' complaints regarding the neck/shoulder and lower back region, fatigue, and feelings of discomfort in the cabin caused basically by a lack of anthropometric compliance and vibrations [7–9]. Awkward postural requirements, including static sitting and repetitive movements in an inadequate position during the work of the operator in the cabins of transport and mining machines, are the result of the inadequate design of the cab or working procedures [10]. In addition to that, the operators' working conditions imply whole-body vibration, psychosocial factors, dust, exhaust gases, noise, temperature extremes, and time pressure, while working in shifts often with prolonged working hours, which also seriously affects the health and working performance of operators [5,11–13]. Additionally, there are recognized visibility issues, the limited space of the cabin, commands/levers reach issues, inadequate seat design, and cab entry/exit problems [3,5,6,14–18]. Non-neutral torso positions involving flexion, lateral flexion, and/or twisting lead to muscle fatigue, spinal compression, lower back intervertebral pressure, and lumbar pain are often presented [10,19,20]. The operators' uncomfortable position implies that backrests and armrests can hardly be used for their purpose [21], and it seems that different kinds of mirrors and smart systems have still not solved those issues [22,23]. Additionally, anthropometric mismatches in cabs are rarely analyzed [5,6]. Regarding mining industry machines, in a similar cab space, there are also dust, noise, exhaust, and dust emissions [24]. In total, it seems that ergonomic risks in contemporary cab designs are numerous and interrelated, while solutions are still far from optimal.

However, although it could be very useful, checklists for cab design evaluation are not common in the literature. One of very few with an application for evaluating the design of construction equipment cabins is developed by Kittusamy [10]. The shortcomings of the list proposed and tested in [10] are the small sample size in which only constructive equipment is included (excavator and loader). Additionally, other instruments should not be neglected, firstly the Nordic Musculoskeletal Questionnaire [7], which focuses on musculoskeletal disorders solely, and the NASA Task Load Index, which has the shortcoming that its weighting does not allow the direct expression of two or more dimensions as equally important [25]. It would be very useful to improve and statistically test the checklist proposed in [10] on a larger sample of heavy mobile machinery operators.

The aim of this paper is to propose a novel checklist that points out the ergonomics risks and statistically validates its measurement structure on the sample of 102 transport, construction, and mining machines, including cranes, excavators, bucket wheel excavators, bulldozers, loaders, graders, backhoe loaders, trenchers, dump trucks, and scrapers. The recognized issues in heavy mobile machinery cabs are interrelated and have never been examined, and this paper aims to explore those relations. Following the introduction provided in Section 1, previous research in the field is presented in Section 2, and the methodology for the statistical testing of the proposed measurement structure is presented in Section 3. Section 4 describes the model testing through statistical data analysis. Section 5 offers a discussion about the obtained results, while Section 6 provides survey conclusions and recommendations for designers.

2. Background

The health issues of heavy mobile machinery are well recognized both in practice and in the literature sources. However, the causes of the health issues of operators are missing in the literature. Even when ergonomic issues as a possible cause of health issues are recognized, they are rarely dealt with, and those empirical study sample sizes are usually small. Small sample sizes further dictate the analysis methods used, so it is not surprising that deep statistical examination and modeling are missing.

Crane operators' occupational health problems caused by cab design are examined rarely, but upper limb and trunk muscle loading and back complaints are often caused by an anthropometric mismatch in non-ergonomic environments. A number of solutions that have been proposed include ergonomically designed and adjustable chairs [5,6,14], adjustable joystick placement, active arm supports and computerized posture monitoring [26], smart vision systems [5], temperature control solutions [5], better controls/levers adjustment to operator [5,6], and also specific coupling systems to prevent vibrations [27]. All studies used small sample sizes—from six cabs by Veljkovic et al. in [28] to 33 cabs by Bundorf and Zonderman in [8].

Construction and mining mobile machinery operators' occupational health problems caused by cab design are focused on occasionally, and there are recognized musculoskeletal disorders, such as lower back pain, felt neck, and knee pains [29], and stiff shoulder issues [25], together with numerous other problems caused by whole-body vibrations [30]. All studies in the field used relatively small sample sizes—from seven cabs by Eger et al. in [31] to 47 cabs by Mandal et al. [29].

Kitusammy [10] proposed a checklist with 31 questions aimed at replacing the time-consuming and complex process of collecting and analyzing postural data. In [32], the authors noticed that there were 540,000 operators of heavy mobile equipment in the United States and only found high levels of postural stress in excavating machine operators. Jorgensen, Kittusamy, and Aedla [11] assessed the repeatability of the cab design checklist on the sample containing 10 different types of heavy mobile equipment, such as excavators, dozers, tower cranes, graders, scrapers, loaders, dump trucks, and concluded that the grader had the best overall cab design, while the skid steer had the worst design. Brkic et al. [5] used a sample of 75 operators and, according to their anthropometric measurements, obtained the minimal dimensions of ergonomically adapted crane cabin interior space. Their sample was considerably larger than all of the samples used so far—Burdorf and Zondervan [8] used a sample of 33 participants, Bovenzi et al. [9] of 46, and Ray and Tewari [33] of 21. Finnes et al. [34] found the organizational climate to be an important factor in musculoskeletal disorders prevention, while Cheberiachko et al. [24] added that mining machinery operators could adequately estimate the situation because of the presence of distracting factors such as noise, dust, exhaust gases, and increased temperature, which further aggravates their psychophysiological state during long working shifts [13]. Accordingly, the checklist proposed in [10] should be extended to cover organizational climate factors such as the atmosphere of cooperation and togetherness, managerial support to operators, and environmental factors such as exhaust gases, dust, and pollution, too. Seat/chair design improvement needs to be recognized in surveys such as [5,6,9,10,33,35]. Armrest issues are diagnosed in surveys [6,9,10,35]. Vibrations are seen as an impeding factor in the literature sources [10,12,17,18]. Control and command usage is ergonomically examined in surveys such as [5,9,10,14]. Cabin space and visibility issues are examined in references [5,6,9,10,14,35]. Employees' interrelations are seen as an important influential factor in safety issues, according to [13,15,36].

3. Materials and Methods

In order to collect the data necessary to model and evaluate ergonomics risks in heavy mobile machinery cabs, the questionnaire was formed on the basis of previous research in the manner that the checklist proposed in [10] and was extended by the findings of surveys [3,5,6,9,12–15,17,18,24,33,35,36], as proposed in the previous section and given in Appendix A. All 39 items were employed besides personal data and had a five-point Likert scale format. Six Serbian companies and heavy mobile machinery operators participated in this study, which lasted from November 2021 to April 2022. Study participants were informed of the objectives of the study and asked to fill in the questionnaire. Participation was entirely voluntary and anonymous. In total, 102 operators of heavy mobile machinery, including cranes, excavators, bucket wheel excavators, bulldozers, loaders, graders, backhoe loaders, trenchers, dump trucks, and scrapers, filled in the questionnaire. All operators in the samples were male, and there were data collected on 29 transport, construction, and mining machine manufacturers. A total of 6.1% of the respondents were categorized as construction machinery operators, 35.6% as crane operators, and the other 58.3% were mining machinery operators. All questions were grouped into six groups: seat characteristics (questions 1–5, 12–14); characteristics of armrests (questions 6–8), whole-body vibrations influence (questions 9–11); reaching commands (questions 15–19); characteristics of cab interior space (questions 20–33); and environment and interpersonal relationships (questions 34–39). Then, correlation analysis, Cronbach's alpha, Spearman-Brown, and Kendall's W coefficient were utilized in order to compare the results of the reliability analysis by all three scales. Exploratory and confirmatory factor analyses were performed with the aim of validating the measurement structure of the proposed checklist. Methodological details are presented in the results section. It is expected to obtain reliable, valid, and as short as possible measurement instruments which describe the possible cab design shortcomings.

4. Results

4.1. Descriptive Statistics

Table 1 shows descriptive data for general questions regarding the characteristics of the operators and machines in the sample, such as the mean, median, minimum, and maximum values, range (R), standard deviation (SD), and coefficient of variation (cv).

Table 1. Descriptive statistics for heavy mobile machinery operators—general questions.

	N	Mean	Med	Min	Max	SD	Cv (%)
Age of operator [year]	102	38.23	37	19	55	9.827	25.7
Height [cm]	102	177.65	178	165	190	6.170	3.5
Weight [kg]	102	89.47	87.5	60	150	15.007	16.8
Working experience [year]	102	13.69	12	1	38	9.809	71.7
Age of machine [year]	102	14.22	9	0	40	14.449	101.6

The criterion for the retaining questions based on a correlation analysis was that the question must have a correlation greater than 0.3 with the other questions within its group [36]. This resulted in the rejection of 18 questions, so questions Q4, Q9, Q10, Q11, Q12, Q14, Q18, Q19, Q20, Q22, Q23, Q24, Q25, Q26, Q29, Q32, Q33, Q36, Q37, and Q38 were deleted from further analysis.

4.2. Reliability and Exploratory Factor Analysis

Reliability is estimated firstly by Cronbach's alpha, as it is suggested in [37] to be the most adequate test for sample sizes of around 100, and the value of the parameter should not be below 0.7 [38]. Additional internal consistency tests, such as Spearman-Brown coefficient, should also be performed according to [39]. Kendall's concordance coefficient W is used to measure the interrater agreement [40]. Cronbach alpha deleted question Q39 from further analysis. In the end, all three measurement scales showed that the data met the scale conditions in every one of them.

Exploratory factor analysis is conducted by Principal component analysis varimax rotation with Kaiser normalization, and values over 0.45 are retained [37,41]. Principal component analysis was chosen because it turns the observed variables into fewer weighted factors, and every additional variable was chosen to explain the greatest share of the variance that was not explained with previous factors, which is not the case in other methods such as the maximum likelihood which represents an estimation method. Varimax rotation with Kaiser normalization provides clearer factor separation than, e.g., Quartimax or Equimax rotation [37]. Exploratory factor analysis included questions Q1, Q2, Q3, Q5, and Q13 into one factor, questions Q15, Q16, and Q17 in the second, questions Q20 and Q21 in the third, questions Q27 and Q28 in the fourth, and questions Q34 and Q35 into the fifth group of factors. It excluded questions Q30 and Q31.

Further results on the reliability, validity and exploratory factor analysis are given in Table 2. The results show adequate values.

Table 2. Results of reliability, validity, and exploratory factor analysis of heavy mobile machinery operators—checklist questions.

Items/Indicators	Cronbach's Alpha	Spearman-Brown Coefficient		Kendall W Coefficient	Factor Loadings
		Equal Length	Unequal Length		
Q1	0.833	0.785	0.791	0.127	0.902
Q2					0.904
Q3					0.819
Q5					0.486
Q13					0.744
Q6	0.972	0.957	0.961	0.000	0.983
Q7					0.973
Q8					0.963
Q15	0.767	0.790	0.806	0.238	0.687
Q16					0.887
Q17					0.898
Q20	0.810	0.810	0.813	0.104	0.825
Q21					0.777
Q27					0.778
Q28					0.807
Q34	0.730	0.730	0.730	0.091	0.887
Q35					0.887

4.3. Confirmatory Factor Analysis

Confirmatory factor analysis was used to verify the measurement of a relationship between the observed variables/indicators/items and their underlying latent constructs [37,41], as in Figure 1 (level of significance $p \leq 0.05$).

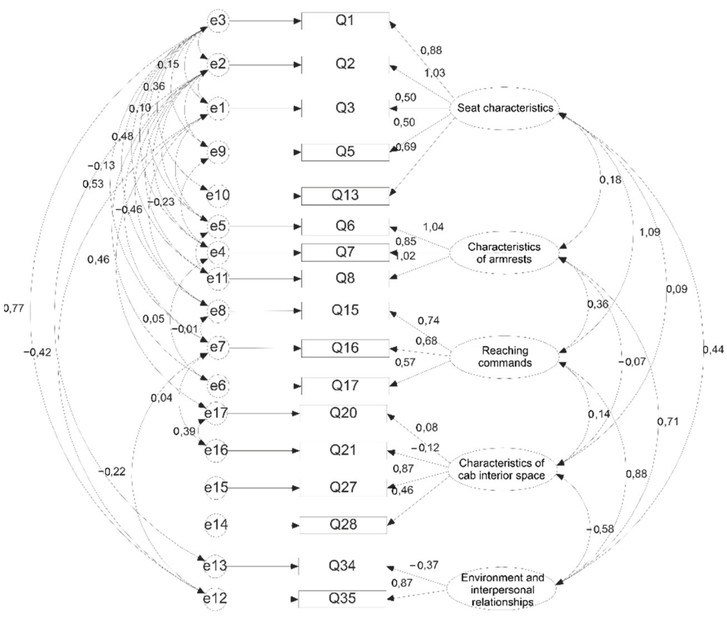

Figure 1. Confirmatory factor analysis model for heavy mobile machinery operators' checklist.

Structural equations matrix, which is describes the model shown in Figure 1 as follows:

$$\begin{bmatrix} Q1 \\ Q2 \\ Q3 \\ Q5 \\ Q13 \\ Q6 \\ Q7 \\ Q8 \\ Q15 \\ Q16 \\ Q17 \\ Q20 \\ Q21 \\ Q27 \\ Q28 \\ Q34 \\ Q35 \end{bmatrix} = \begin{bmatrix} 0.88 & 0 & 0 & 0 & 0 \\ 0.93 & 0 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0 \\ 0.69 & 0 & 0 & 0 & 0 \\ 0 & 0.94 & 0 & 0 & 0 \\ 0 & 0.85 & 0 & 0 & 0 \\ 0 & 0.92 & 0 & 0 & 0 \\ 0 & 0 & 0.74 & 0 & 0 \\ 0 & 0 & 0.68 & 0 & 0 \\ 0 & 0 & 0.57 & 0 & 0 \\ 0 & 0 & 0 & 0.08 & 0 \\ 0 & 0 & 0 & -0.12 & 0 \\ 0 & 0 & 0 & 0.87 & 0 \\ 0 & 0 & 0 & 0.46 & 0 \\ 0 & 0 & 0 & 0 & -0.37 \\ 0 & 0 & 0 & 0 & 0.87 \end{bmatrix} \cdot \begin{bmatrix} \text{Seat characteristics} \\ \text{Characteristics of armrests} \\ \text{Reaching commands} \\ \text{Characteristics of cab interior space} \\ \text{Environment and interpersonal relationships} \end{bmatrix} + \begin{bmatrix} 0.252 \\ -0.065 \\ 1.333 \\ 1.888 \\ 0.664 \\ -0.010 \\ 0.044 \\ -0.013 \\ 0.691 \\ 0.273 \\ 0.363 \\ 1.424 \\ 0.470 \\ 0.133 \\ 0.836 \\ 0.709 \\ 0.086 \end{bmatrix}$$

In Table 3, satisfactory fit indices can be seen.

Table 3. Fit indices for confirmatory factor analysis model for heavy mobile machinery operators—checklist questions.

Fit Indices	Recommended Values [37,42]	Values in the Model
χ^2	-	118.3
df	-	66
χ^2 significance p	≤0.001	0.0000
χ^2/df	<3.0 “good” <5.0 “permissible”	1.7924
GFI (Goodness of Fit)	>0.9 or >0.8	0.918
AGFI (Adjusted Goodness of Fit)	>0.9 or >0.8	0.817
NFI (Normed Fit Index)	>0.90	0.901
CFI (Comparative Fit Index)	>0.90	0.963
TLI (Tucker–Lewis Index)	>0.90	0.929
RMSEA (Root Mean Square Error of Approximation)	≤0.05 “very good fit” 0.05–0.08 “good fit” 0.08–0.10 “moderate fit” >0.10 “bad fit”	0.070

5. Discussion

The research was conducted in Serbia on the heavy mobile machinery manufactured by 29 manufacturers and used by 102 operators providing a very good basis for the evaluation of cranes’, excavators’, bucket wheel excavators’, bulldozers’, loaders’, graders’, backhoe loaders’, trenchers’, dump trucks, and scrapers’ cab designs. The measurement model is designed on the basis of collected data, and the relationship between the measurement indicators and latent variables is established through multivariate analysis.

The results show that significant latent factors in mobile heavy machinery cab design are seat characteristics, the characteristics of armrests, reaching commands, characteristics of cab interior space, environment, and interpersonal relationships. It is evident that whole-body vibrations, which have been often examined in previous research, seem to be solved by the manufacturers since they are not part of the validated measurement model. Additionally, foot controls also seem well designed (not in the model). Important seat characteristics are the seat's vertical and horizontal adjustability, the seat height, the possibility that the seat can be tilted back, and its lumbar support. Additionally, it is important to have armrests, to enable their adjustability and to put them to an appropriate height. The location of the controls or levers should be adjustable; it is important to easily reach and move the controls or levers. The cab interior space has to be adjusted to the operator's anthropometric measurements in a manner that the cab interior space will be large enough and enable good visibility in all directions. Additionally, the entrance and exit into the cab have to be solved in a manner that means the operator can easily move in and out of the cab. It has been obtained that interpersonal relations are not helpful in any sense that could diminish certain design issues, while the working conditions and especially exhaust gases and dust, are important in cab design to prevent the operators' absence from work.

The results of the reliability analysis showed that according to all three scales, Cronbach's alpha, Spearman-Brown coefficient, and Kendall W coefficient data are reliable. High values of Cronbach's alpha indicated that the observed sample is valid.

The performed exploratory factor analysis showed that factor loading of all observed variables has a high value that indicates that all variables participate and have a large impact on the factor in which they are distributed.

The confirmatory factor analysis results show that fit indices are in line with the recommended values.

Our results prove numerous hints in the previous research, but they are not aligned with those by Carayon et al. [36] and Finnes et al. [34], which have expected improvements in teamwork and organizational climate for tools with the potential to reduce musculoskeletal disorders. The highest values of the path coefficients have questions 2,6, and 8, so special attention should be drawn to horizontal seat adjustment, and armrests are a must and should be put at the appropriate height. It could be seen that all groups of the questions were positively correlated besides the characteristics of armrests and the environment and interpersonal relationships vs. cab interior space. So, special attention should be paid to the design of armrests as well as the environment and interpersonal relationships. Accordingly, the designers can make significantly better judgments if they look at each pair of risk factors, as proposed in [43].

6. Conclusions

Heavy mobile machinery, even after continual design improvements over decades and numerous and various manufacturers' efforts in that aim, still cause huge losses at sites where they are working all over the world. Both operators and other workers are still exposed to numerous risks due to the inadequate consideration of ergonomic principles in cab designs. Numerous previous research reported the ergonomic inconvenience of heavy mobile machines' cabins and pointed out the necessary improvements. Evaluation is a necessary predecessor step before the design improvement process, and checklists are very useful but rarely used for that aim.

This paper proposed a novel checklist and validated its measurement structure. It was conducted by correlation analysis, Cronbach's alpha, Spearman-Brown and Kendall's W coefficient, exploratory factor analysis, and confirmatory factor analysis. Our results validate the measurement structure with five constructs, namely, seat characteristics, the characteristics of armrests, reaching commands, characteristics of cab interior space and environment, and interpersonal relationships, while the influence of the whole-body vibrations is not validated.

According to our results, the following recommendations could be given:

- Designers should put special attention to 17 characteristics (the seat's vertical and horizontal adjustability, the seat height, the possibility that the seat can be tilted back, and its lumbar support; armrests should exist and should be adjustable and put to an appropriate height; the location of the controls or levers should be adjustable, and should be easily reached and moved; the cab interior space should be large enough and enable good visibility from the cab in all directions, while both the entrance and exit into the cab need to be carefully solved; working conditions and especially exhaust gases and dust are important in cab design to prevent the operators' absence from work). These are grouped as seat characteristics, characteristics of armrests, reaching commands, characteristics of cab interior space, and environmental factors.

- In the current examined designs, whole-body vibration issues and controls according to the model obtained seem well solved.
- Special attention should be drawn to the horizontal adjustment of the seat, armrests are a must, and they should be put at the appropriate height.
- Since all groups of questions are positively correlated (which means that improvements in one area lead to improvements in another), besides the characteristics of armrests and environment and interpersonal relationships vs. cab interior space, special attention should be paid to the design of armrests and environment and interpersonal relationships.

Further research should include continuous data collection and analysis due to changes in the designs and operators' anthropometric measurements over time, and even larger samples than in this survey are recommended. For the further safe and efficient design of heavy mobile machines' cabins, it is recommended to use the proposed checklist as a quick, reliable, and cost-effective method instrument as the first step in design changes and continual improvements.

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Appendix A

Questionnaire for Heavy Mobile Machinery Operators.

General information about the operator and machine operated:

1. Age of the operator
2. Operator height (cm)
3. Operator weight (kg)
4. Years of work experience
5. Machine-operated type and producer
6. Age of the machine operated (years)

Checklist

For each question asked circle the number on a scale from 1 to 5, depending on whether you think that the characteristic you are evaluating is bad or does not exist (grade 1) or if there is an exceptional one (grade 5).

1. Is the seat height adjustable?	1	2	3	4	5
2. Can the seat be adjusted horizontally?	1	2	3	4	5
3. Is the seat set at the appropriate height?	1	2	3	4	5
4. Does the seat have back support?	1	2	3	4	5
5. Does the seat have lumbar support?	1	2	3	4	5
6. Are there armrests?	1	2	3	4	5
7. Are the armrests adjustable?	1	2	3	4	5
8. Are the armrests set at the appropriate height?	1	2	3	4	5
9. Do you feel vibrations over the seat?	1	2	3	4	5
10. Do you feel vibrations over the floor?	1	2	3	4	5
11. Do you feel the vibrations through the controls?	1	2	3	4	5
12. Is the seat firmly attached to the cab floor?	1	2	3	4	5
13. Can the seat be tilted back?	1	2	3	4	5
14. Can the seat rotate?	1	2	3	4	5
15. Can the location of the controls or levers be adjusted?	1	2	3	4	5
16. Can you easily reach the controls or levers?	1	2	3	4	5
17. Can you easily move the controls or levers?	1	2	3	4	5
18. Can you easily reach the pedal?	1	2	3	4	5
19. Can you use the pedal easily?	1	2	3	4	5
20.Is the cabin large/spacious enough for you?	1	2	3	4	5
21. Do you have enough visibility in all directions?	1	2	3	4	5
22. Is your view of ongoing operation obstructed by obstacles?	1	2	3	4	5
23. Do you hear noise in the cabin?	1	2	3	4	5
24. Can you control the temperature in the cabin?	1	2	3	4	5
25. Does the cabin equipment have sills?	1	2	3	4	5
26. Does the equipment have handrails?	1	2	3	4	5
27. Can you easily open/close the cabin door?	1	2	3	4	5
28. Can you easily get in/out of the cab?	1	2	3	4	5
29. Do you have the proper equipment to enter the cabin?	1	2	3	4	5
30. Do you have the proper equipment to get out of the cabin?	1	2	3	4	5
31. Do you have good visibility and a general view of the work area?	1	2	3	4	5
32. Are the cabin windows without distraction?	1	2	3	4	5
33. Is there a device that allows better visibility of the working field?	1	2	3	4	5
34. Due to poor working conditions, I am often absent from work (sick leaves).	1	2	3	4	5
35. Do exhaust gases and dust bother you?	1	2	3	4	5
36. Do you mind pollution that is part of working conditions?	1	2	3	4	5
37. The atmosphere of cooperation and togetherness prevails among the operators.	1	2	3	4	5
38. Managers motivate and reward us.	1	2	3	4	5
39. Machine failures are very often caused by human and organizational factors.	1	2	3	4	5

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