Proceedings of the Estonian Academy of Sciences
2025, **74**, 2, 137–142

https://doi.org/10.3176/proc.2025.2.09

www.eap.ee/proceedings
Estonian Academy Publishers

OPTIMIZATION; MULTI-CRITERIA DECISION-MAKING METHODS

RESEARCH ARTICLE

Received 30 January 2025
Accepted 27 February 2025
Available online 9 April 2025

Keywords:
conceptual framework for safety/risk analysis, multi-criteria decision-making methods, ranked risks

Corresponding author:
Johannes Matsulevitš
johannes.matsulevits@taltech.ee

Citation:
Matsulevitš, J., Majak, J., Eerme, M., Sarkans, M., Dunajeva, O., Kristjuhan-Ling, K. et al. 2025. Human-robot interaction: a conceptual framework for safety/risk analysis. *Proceedings of the Estonian Academy of Sciences*, **74**(2), 137–142. https://doi.org/10.3176/proc.2025.2.09

Human-robot interaction: a conceptual framework for safety/risk analysis

Johannes Matsulevitš[a], Jüri Majak[a], Martin Eerme[a], Martinš Sarkans[a], Olga Dunajeva[b], Kadri Kristjuhan-Ling[a], Tõnis Raamets[a] and Vjatšeslav Kekšin[a]

[a] Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

[b] Virumaa College, Tallinn University of Technology, Järveküla tee 75, 30322 Kohtla-Järve, Estonia

ABSTRACT

From smart factories to service applications, human-robot interaction is crucial to the development of collaborative settings in which humans and robots operate side by side. Since robots in shared spaces must take into consideration variables such as human motion unpredictability and potential workplace risks, effective risk management is essential. When building these systems, striking a balance between factors such as safety, ergonomics, and operational flexibility becomes crucial. Misalignment between human purpose and robot behaviors might result in accidents or increased injury risks, especially in environments with high physical demands. One of the key challenges in human-robot interaction is handling uncertainty.

The main aim of the current study is to introduce a conceptual framework for safety/risk analysis, including a hierarchy tree of the risk criteria and risks. Both human- and robot-related factors are considered. The multi-criteria decision-making procedure developed for autonomous vehicle systems is adapted for risk analysis in human-robot interaction. As a final result, the prioritized risk criteria and risks are identified. These results lay the foundation for reducing risks in the future.

1. Introduction

Industry 5.0 seeks to surpass traditional manufacturing methods by developing interconnected systems that seamlessly integrate machinery, robots, workers, products, and consumers. Human centricity, personalization, sustainability, and trust are among the primary contrasts between Industry 4.0 and Industry 5.0 [1]. A comprehensive review of human-robot collaboration (HRC) within the context of Industry 4.0 is given in [2], identifying key trends and challenges. The advantages and limitations of collaborative robots are discussed, pointing out flexibility and productivity on the positive side, and complexity of integration and safety concerns on the negative side. In [3], dynamic risk assessment is performed by applying active response strategies in HRC. This approach dynamically assesses the risks associated with human-robot interactions (HRI) and highlights the critical role of adaptive systems in mitigating the risks. A multi-criteria approach to designing HRC systems, which balances human and robot capabilities and incorporates ergonomic, economic, and operational factors, was introduced in [4]. In [5], multi-criteria decision-making (MCDM) is used to analyze factors influencing HRI. By leveraging MCDM, this study provides a structured approach to facilitating decision-making in complex industrial scenarios. In [6], an approach based on a Fuzzy AHP (analytical hierarchy process) and Fuzzy TOPSIS (technique for order of preference by similarity to ideal solution) is developed for safety/risk analysis for an automated vehicle shuttle. In [7], a survey is given on human behavior modeling techniques within HRC contexts. In [8,9], the advancements in HRC are studied, covering safety, ergonomics, efficiency, and adaptability. The relationship between lighting and human performance, comfort, and well-being in HRI is explored in [10], while the integration of ergonomics into business processes is discussed in [11]. The challenges in aligning vocational training with rapidly evolving technologies are discussed in [12]. The complexities of HRI are studied in [13], with focus on trust, reliability, and adaptability. The ethical challenges and implications of emerging technologies in HRI are explored in [14,15]. A conceptual framework for task performance analysis is given in [16], where the main focus is on productivity, time, and accuracy. Obviously, one possible approach is to handle task performance and risks simultaneously.

However, herein, a different approach is proposed, which is based on a decompositon method. According to this approach, first, safety assessment is performed, determining the most critical risks. Subsequently, risk mitigation actions are implemented for critical risks, and as the last step, performance analysis/optimization is executed. The current study is focused on the first step – safety assessment in HRI. A conceptual framework for safety/risk analysis is introduced, including a hierarchy tree of the risk criteria and risks. To ensure consistent human safety in HRI, human- and robot-related factors are considered. The current workgroup has long-term experience with the development and application of MCDM methods and artificial intelligence (AI)-based optimization methods for a wide class of engineering design problems [17–21]. In [18], Fuzzy AHP (FAHP) was utilized for environmental, social, and governance risk assessment in phosphorite mining. In the following, the FAHP and Fuzzy TOPSIS methods are combined for evaluating the risk criteria and risks in HRI. The selection of MCDM is justified by its lower implementation and computational complexities compared to other powerful multi-criteria risk analysis methods, such as Monte Carlo and global optimization methods.

2. Conceptual framework for safety/risk analysis

Obviously, safety is the most critical or one of the most critical issues in any form of HRI. Based on the literature introduced above and on the previous experience of the workgroup on safety analysis of robotic systems, herein, the conceptual framework for safety/risk analysis is introduced (see Fig. 1).

The description of the human- and robot-related factors is introduced and discussed in [6,16]. The main components of the safety/risk analysis framework are discussed below.

3. Risk criteria and risks

The risk criteria and risks are introduced in a number of papers for robotic systems [4–6]. In [16], the human-related factors are introduced and analyzed for task performance analysis in HRI. Below, risk criteria (Table 1) and risks (Fig. 2) are introduced, proceeding from safety/risk issues in HRI.

For the sake of conciseness, the risks corresponding to the above criteria are summarized in a decision hierarchy tree shown in Fig. 2.

The risks considered in Fig. 2 are the following: R11 – tiredness and fatigue, R12 – particular health problems, R13 – stress, R21 – insufficient skills, R22 – insufficient know-how, R31 – safety control system failure, R32 – speed limit exceedance, R33 – minimum distance violation, R34 – force/power limits violation, R35 – emergency stop not working, R41 – bad previous experience, R42 – negative prejudice, R43 – lack of trust, R44 – vigilance, R45 – unpredictable

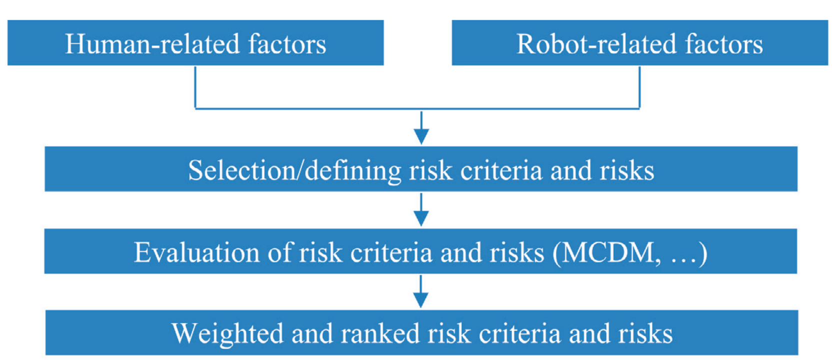

Fig. 1. Conceptual framework for safety/risk analysis.

Table 1. Human-robot interaction: risk criteria

Risk criterion	Description
Occupational safety and health (C1) [8,9,22,23]	Occupational safety and health (OSH) in HRI covers the mental and physical safety and the ergonomic suitability of robots for operators who interact in common workplace environments. This criterion helps to prevent workplace injuries and reduce health risks. These standards provide a framework for improving workplace safety, including interactions with robots.
Professional preparation (C2) [9]	Professional preparation covers continuous learning and skill development in order to keep employees qualified and competitive as robotic systems and AI are in continuous development. Employees must learn how to work collaboratively with robots and understand robotic behaviors.
Physical issues (C3) [8,10,11]	Physical issues in HRI cover physical safety and comfort of humans working in a common workplace. Particularly, collision or maximum speed avoidance, force limitations violations, etc., are considered. The environmental factors are included as well (noise, lighting). The workplace design should allow for smooth HRC.
Psychological issues and trust (C4) [12,13]	Trust in HRI mirrors the acceptance of robots in human environments, particularly in a common workplace. Here, a lack of trust can lead to limited cooperation in HRI, but excessive trust may lead to unnecessary safety risks. Psychological issues in HRI are related to mental stress, human acceptance of robotic systems, the influence of robotic systems, and uncertainty in the robot's actions.
Ethical and legal issues (C5) [14,15]	Ethical and legal issues in HRI address moral principles and legal frameworks covering the development and application of robotic systems. The risks related to ethical and legal issues include privacy violations, data misuse, and non-compliance with legal standards.

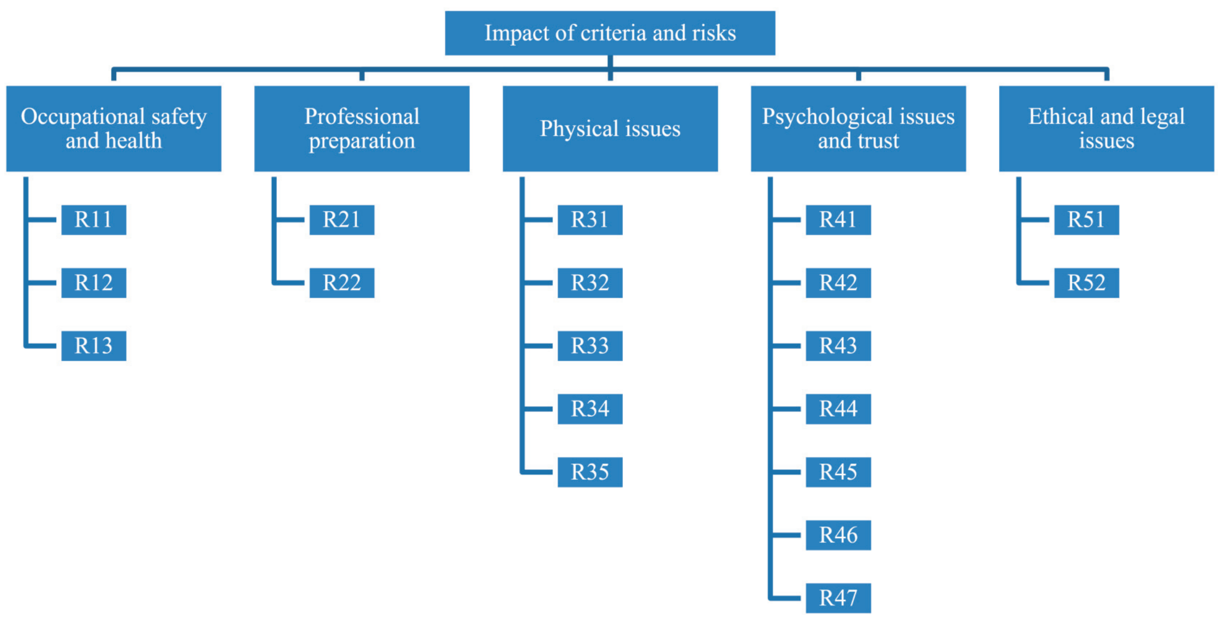

Fig. 2. Decision hierarchy tree for safety/risk analysis in HRI.

robot motion, R46 – misplaced trust, R47 – overreliance on robots, R51 – privacy violations, and R52 – data misuse, non-compliance with regulations.

4. Evaluation of criteria and risks

Herein, powerful AI-based MCDM methods are utilized for the prioritization of the criteria and risks. Particularly, FAHP with triangular fuzzy numbers (TFN) is utilized for the prioritization of the criteria, and Fuzzy TOPSIS is used for the prioritization of the risks. In the following, the evaluation procedure introduced in [6] for the prioritization of the risks of an automated vehicle shuttle is adapted for risk analysis in HRI.

4.1. Evaluation of the risk criteria

The evaluation of the risk criteria is based on the pairwise comparison of the criteria using linguistic variables. Implementing fuzzy numbers fundamentally simplifies the work of decision-makers

Table 2. Pairwise comparison matrix of risk criteria

	C1	C2	C3	C4	C5
Occupational safety and health (C1)	EqP	MP	1/M-SP	SP	SP-VSP
Professional preparation (C2)	1/MP	EqP	1/M-SP	SP	SP
Physical issues (C3)	M-SP	M-SP	EqP	SP	SP-VSP
Psychological issues and trust (C4)	1/SP	1/SP	1/SP	EqP	MP
Ethical and legal issues (C5)	1/SP-VSP	1/SP	1/SP-VSP	1/MP	EqP

Table 3. Aggregated pairwise comparison matrix in terms of fuzzy numbers

	C1	C2	C3	C4	C5
C1	(1.00,1.00,1.00)	(2.12,3.17,4.20)	(0.26,0.32,0.42)	(3.84,4.84,5.85)	(4.99,6.01,6.92)
C2	(0.24,0.32,0.47)	(1.00,1.00,1.00)	(0.21,0.27,0.37)	(3.68,4.72,5.75)	(3.99,5.02,6.04)
C3	(2.38,3.12,3.83)	(2.74,3.77,4.79)	(1.00,1.00,1.00)	(3.34,4.36,5.37)	(4.94,5.95,6.96)
C4	(0.17,0.21,0.26)	(0.17,0.21,0.27)	(0.19,0.23,0.30)	(1.00,1.00,1.00)	(1.92,2.95,3.96)
C5	(0.14,0.17,0.20)	(0.17,0.20,0.25)	(0.14,0.17,0.20)	(0.25,0.34,0.52)	(1.00,1.00,1.00)

Table 4. Fuzzy and crisp weights of the criteria, final ranks

	Aggregated fuzzy comparison values	Fuzzy weights	Crisp weights	Normalized crisp weights	Rank
C1	(1.60,1.97,2.35)	(0.19,0.28,0.41)	0.29	0.28	2
C2	(0.94,1.15,1.43)	(0.11,0.16,0.25)	0.17	0.17	3
C3	(2.55,3.14,3.69)	(0.30,0.45,0.64)	0.46	0.44	1
C4	(0.40,0.49,0.61)	(0.05,0.07,0.11)	0.07	0.07	4
C5	(0.24,0.29,0.35)	(0.03,0.04,0.06)	0.04	0.04	5

(a group of seven industry and academic experts), replacing fixed-point estimates with interval estimates. A sample of one decision-maker's estimates is given in Table 2 (a detailed description of the linguistic variables used is given in [18]).

According to the FAHP procedure introduced in [6], the estimates given in Table 2 are converted to fuzzy numbers and aggregated by utilizing the geometric mean (see Table 3).

Next, the fuzzy comparison values r_i and fuzzy weigths w_i are computed:

$$r_i = \left(\prod_{j=1}^{N_{crit}} r_{ij}\right)^{1/N_{crit}},\ w_i = (l_i, m_i, u_i) = r_i \otimes (r_1 \oplus r_2 \oplus \ldots \oplus r_{Ncrit})^{-1}, \ldots i = 1, \ldots, Ncrit, \quad (1)$$

where $\oplus$ and $\otimes$ stand for the addition and multiplication operators with triangular fuzzy numbers, r_{ij} and N_{crit} are the fuzzy comparison matrix elements and the number of criteria, respectively. The centroid method is utilized for defuzzification. The ranking is performed based on crisp weights. The results are given in Table 4.

4.2. Evaluation of the risks

In the following, the Fuzzy TOPSIS approach introduced by the authors in [6] is utilized for risk evaluation. In compact form, the main steps of the risk evaluation procedure can be given as follows:

- Pairwise comparison of risks vs. criteria in terms of linguistic variables
- Transforming linguistic values to fuzzy numbers and computing the aggregated matrix using the arithmetic mean
- Computing the weighted normalized decision matrix using the fuzzy weights of the criteria
- Computing the distances of each risk to the positive and negative ideal solutions, and the similarity index
- Ranking risks based on the similarity index

The distances to the positive and negative ideal solutions, the similarity index, and the ranks of the risks are presented in Table 5 as the final results.

Table 5. Final ranking of the risks

	D+	D–	Similarity index (C)	Rank
R11	0.72	0.30	0.296	6
R12	0.81	0.22	0.212	8
R13	0.75	0.28	0.269	7
R21	0.86	0.16	0.156	9
R22	0.94	0.07	0.070	11
R31	0.60	0.45	0.426	3
R32	0.63	0.42	0.402	5
R33	0.59	0.46	0.436	1
R34	0.61	0.44	0.416	4
R35	0.59	0.45	0.433	2
R41	0.96	0.05	0.048	15
R42	0.96	0.05	0.047	16
R43	0.94	0.06	0.063	13
R44	0.95	0.06	0.055	14
R45	0.93	0.08	0.075	10
R46	0.97	0.03	0.030	18
R47	0.94	0.07	0.066	12
R51	0.99	0.02	0.016	19
R52	0.97	0.04	0.037	17

5. Conclusion

While the performance and risk analysis of robotic systems has been extensively studied, the analysis of human-robot interaction in terms of performance and risk remains comparatively less explored.

The current study is focused on safety assessment in HRI. The main contribution of this paper is the development of a conceptual framework for safety/risk analysis, involving the selection of risk criteria and risks in HRI and their evaluation. The Fuzzy AHP- and Fuzzy TOPSIS-based risk evaluation procedure developed provides a simple and powerful tool for risk prioritization. The values of the similarity indices provide more information than simply the ranking of risks, as they also reflect differences in the magnitudes of risks (see Table 5).

Data availability statement

All data are available in the article.

Acknowledgments

This article was funded by the European Regional Development Fund and supported by the project "Increasing the knowledge intensity of Ida-Viru entrepreneurship", funded by the European Union. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

References

1. Raffik, R., Vaishali, V., Balavedhaa, S., Jyothi Lakshmi, N. and Sathya, R. R. Industry 5.0: enhancing human-robot collaboration through collaborative robots – a review. In *2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA), Coimbatore, India, 16–17 June 2023*. IEEE, 2023, 1–6. https://doi.org/10.1109/ICAECA56562.2023.10201120
2. Baratta, A., Cimino, A., Gnoni, M. G. and Longo, F. Human robot collaboration in Industry 4.0: a literature review. *Procedia Comput. Sci.*, 2023, **217**, 1887–1895. https://doi.org/10.1016/j.procs.2022.12.389
3. Zhang, W., Jia, X., Liu, J., Zhang, S. and Li, T. Dynamic risk assessment and active response strategy of human-robot collaboration based on fuzzy comprehensive evaluation. *Robot. Comput. Integr. Manuf.*, 2024, **88**, 102732. https://doi.org/10.1016/j.rcim.2024.102732
4. Papetti, A., Ciccarelli, M., Scoccia, C. and Germani, M. A multi-criteria method to design the collaboration between humans and robots. *Procedia CIRP*, 2021, **104**, 939–944. https://doi.org/10.1016/j.procir.2021.11.158
5. Bhalaji, R. K. A., Bathrinath, S., Ponnambalam, S. G. and Saravanasankar, S. Analyze the factors influencing human-robot interaction using MCDM method. *Mater. Today Proc.*, 2021, **39**(P1), 100–104. https://doi.org/10.1016/j.matpr.2020.06.316
6. Pikner, H., Sell, R., Majak, J. and Karjust, K. Safety system assessment case study of automated vehicle shuttle. *Electronics*, 2022, **11**(7), 1162. https://doi.org/10.3390/electronics11071162
7. Jahanmahin, R., Masoud, S., Rickli, J. and Djuric, A. Human-robot interactions in manufacturing: a survey of human behavior

modeling. *Robot. Comput. Integr. Manuf.*, 2022, **78**, 102404. https://doi.org/10.1016/j.rcim.2022.102404
8. Villani, V., Pini, F., Leali, F. and Secchi, C. Survey on human–robot collaboration in industrial settings: safety, intuitive interfaces and applications. *Mechatronics*, 2018, **55**, 248–266. https://doi.org/10.1016/j.mechatronics.2018.02.009
9. Ajoudani, A., Zanchettin, A. M., Ivaldi, S., Albu-Schäffer, A., Kosuge, K. and Khatib, O. Progress and prospects of the human–robot collaboration. *Auton. Robots*, 2018, **42**(5), 957–975. https://doi.org/10.1007/s10514-017-9677-2
10. Boyce, P. R. *Human Factors in Lighting.* 3rd ed. CRC Press, 2014. https://doi.org/10.1201/b16707
11. Dul, J. and Neumann, W. P. Ergonomics contributions to company strategies. *Appl. Ergon.*, 2009, **40**(4), 745–752. https://doi.org/10.1016/j.apergo.2008.07.001
12. Gekara, V. and Snell, D. Designing and delivering skills transferability and employment mobility: the challenges of a market-driven vocational education and training system. *J. Voc. Educ. Train.*, 2018, **70**(1), 107–129. https://doi.org/10.1080/13636820.2017.1392996
13. Hancock, P. A., Billings, D. R., Schaefer, K. E., Chen, J. Y. C., de Visser, E. J. and Parasuraman, R. A meta-analysis of factors affecting trust in human-robot interaction. *Hum. Factors*, 2011, **53**(5), 517–527. https://doi.org/10.1177/0018720811417254
14. Voigt, P. and von dem Bussche, A. *The EU General Data Protection Regulation (GDPR). A Practical Guide*. Springer, 2017.
15. Floridi, L. and Taddeo, M. What is data ethics? *Phil. Trans. R. Soc. A*, 2016, **374**, 20160360. https://doi.org/10.1098/rsta.2016.0360
16. Di Pasquale, V., Farina, P., Fera, M., Gerbino, S., Miranda, S. and Rinaldi, M. Human robot-interaction: a conceptual framework for task performance analysis. *IFAC PapersOnLine*, 2024, **58**(19), 79–84. https://doi.org/10.1016/J.IFACOL.2024.09.096
17. Mehrparvar, M., Majak, J. and Karjust, K. A comparative analysis of Fuzzy AHP and Fuzzy VIKOR methods for prioritization of the risk criteria of an autonomous vehicle system. *Proc. Estonian Acad. Sci.*, 2024, **73**(2), 116–123. https://doi.org/10.3176/proc.2024.2.04
18. Paat, A., Majak, J., Karu, V. and Hitch, M. Fuzzy analytical hierarchy process based environmental, social and governance risks assessment for the future phosphorite mining in Estonia. *Extr. Ind. Soc.*, 2024, **17**, 101438. https://doi.org/10.1016/j.exis.2024.101438
19. Kaganski, S., Majak, J. and Karjust, K. Fuzzy AHP as a tool for prioritization of key performance indicators. *Procedia CIRP*, 2018, **72**, 1227–1232. https://doi.org/10.1016/j.procir.2018.03.097
20. Paavel, M., Karjust, K. and Majak, J. Development of a product lifecycle management model based on the fuzzy analytic hierarchy process. *Proc. Estonian Acad. Sci.*, 2017, **66**(3), 279–286. https://doi.org/10.3176/proc.2017.3.05
21. Bassir, D., Lodge, H., Chang, H., Majak, J. and Chen, G. Application of artificial intelligence and machine learning for BIM: review. *Int. J. Simul. Multidisci. Des. Optim*., 2023, **14**, 5. https://doi.org/10.1051/smdo/2023005
22. EVS-EN ISO 45001:2023. *Occupational health and safety management systems – Requirements with guidance for use*.
23. ISO/TS 15066:2016. *Robots and robotic devices – Collaborative robots*.

Inimese ja roboti koostöö: ohutuse ja riskianalüüsi kontseptuaalne raamistik

Johannes Matsulevitš, Jüri Majak, Martin Eerme, Martinš Sarkans, Olga Dunajeva, Kadri Kristjuhan-Ling, Tõnis Raamets ja Vjatšeslav Kekšin

Tarkade tehaste ja teenuste valdkonnas, kus inimesed ja robotid töötavad kõrvuti, on nende koostöö arendamine esmatähtis. Tõhus riskijuhtimine on hädavajalik, kuna robotid peavad arvestama inimeste liikumise ja potentsiaalsete töökeskkonna ohtudega. Selliste süsteemide loomisel on väga oluline ohutuse, ergonoomika ja paindlikkuse vahelise tasakaalu leidmine. Ebakõla inimese liikumise ja roboti käitumise vahel võib põhjustada õnnetusi või suurendada vigastuste riski. Üks keeruline aspekt inimeste ja robotite koostöös on määramatusega arvestamine.

Artiklis tutvustatakse ohutuse ja riskianalüüsi kontseptuaalset raamistikku, mis sisaldab riskikriteeriumide ja riskide hierarhiat. Arvesse võetakse nii inimeste kui ka robotitega seotud tegureid. Autonoomsete sõidukite jaoks välja töötatud multikriteriaalset otsustusprotsessi kohandatakse inimeste ja robotite koostöö riskianalüüsiks. Lõpptulemusena saadakse olulisuse alusel järjestatud kriteeriumid ja riskid, mis loob võimaluse riskide vähendamiseks tulevikus.