A MCDM-based methodology to evaluate the mutual influence among performance shaping factors

Adelfio L.*, La Scalia G.*, La Fata C.M.*, Giallanza A. *, Micale R. * *

** Department of Engineering, University of Palermo Viale delle Scienze bld 8, 90128, Palermo – Italy (luca.adelfio@unipa.it, Giada.lascalia@unipa.it, concettamanuela.lafata@unipa.it, antonio.giallanza@unipa.it)*

*** Department of Engineering, University of Messina, Contrada di Dio, 98166, Messina – Italy (rosa.micale@unime.it)*

Abstract: In recent decades, risk analysts have widely focused on Human Reliability Analysis (HRA) methods to assess the contribution of human errors to system failures, also considering contextual and cognitive factors named Performance Shaping Factors (PSFs). Initially implemented in the field of Nuclear Power Plants (NNPs), HRA methods have been extended to different sectors in recent years. Despite that, the majority of contributions in the field assume the independence among PSFs, which may result in an over or under estimation of the Human Error Probability (HEP). Therefore, the present paper proposes a DEMATEL-based approach to evaluate the mutual influence between PSFs proposed by the SPARH method. A case study related to the agri-food sector is presented.

Keywords: Human Reliability Analysis (HRA); Human Error Probability (HEP); Performance Shaping Factors (PSFs); DEMATEL.

I. INTRODUCTION

In recent decades, human reliability has been recognized to play a prominent role in risk assessment. In fact, about 70-90% of accidents - in different fields - arise from human errors, while the remainder is to be found in technical reasons [1,2]. Aiming to quantify the Human Error Probability (HEP) in critical situations, the first Human Reliability Analysis (HRA) methodologies were implemented in Nuclear Power Plants (NPPs) in the seventies, while their extension to other sectors has started in recent years [3,4,5,6]. First generation HRA methods (e.g. Technique for Human Error Rate Prediction - THERP and Success Likelihood Index Method – SLIM) [7,8] simply consider the human being as an electronic or mechanical component characterized by his/her own failure rate. On the other hand, second generation HRA methods (e.g. Cognitive Reliability and Error Analysis Method – CREAM, Standardized Plant Analysis Risk-Human reliability analysis - SPARH) [9, 10] are generally based on a double step analysis to compute the HEP when performing a task. It includes both the computation of the Nominal HEP (NHEP) and the assessment of individual, contextual and cognitive factors, named Performance Shaping Factors (PSFs). Used to characterize the specific context where the task is performed, PSFs consist of individual characteristics of workers, working conditions and organizational issues that may influence the workers' performance [11]. Nevertheless, almost all PSFs-based methods disregard the dependence between PSFs, although empirical evidence shows that overlaps and reciprocal influences may occur. [12,13,14]. As a result, this could lead to an incorrect calculation of HEP. Only few contributions provide qualitative guidelines (e.g. SPARH and CREAM) or quantitative approaches to take into account the mutual influence between PSFs [15,12,3,16]. While qualitative methods are not well structured, the quantitative ones are computationally complex or based on statistical analyses requiring a lot of data to be collected over the time [12,15,16,17]. In this regard, two different statistical methodologies based on correlation analysis are proposed by Groth [15] and Boring [12] to quantify the correlation degree among PSFs. Referring to air traffic control room operations, De Ambroggi and Trucco [3] propose the Analytical Network Process (ANP) to take into account both the direct and indirect influences among PSFs. Kyriakidis et al. [18] combine ANP and SLIM techniques to evaluate PSF dependencies in the railway operations field. Finally, La Fata et al. [19] propose a SPARH based approach to calculate the human contribution to risks in a manufacturing context, also considering the mutual influence among PSFs.

Differently from the aforementioned literature, the DEcision MAking Trial and Evaluation Laboratory

(DEMATEL) method [20,21,22] is here proposed to assess both the influence degree and the relative importance of PSFs suggested by SPARH. In particular, DEMATEL combines the extreme simplicity of application with a clear representation of the results. Furthermore, its efficacy in addressing complex decision making problems has been testified over and over again by numerous studies [22,23,24]. The proposed methodology is implemented in the agri-food sector.

The remainder of the paper is organized as follows. Section II provides a brief overview on the SPAR-H method, whereas section III presents the main steps of DEMATEL. Finally, the application case and the conclusions are reported in sections IV and V respectively.

II. SPARH METHOD OVERVIEW

SPARH was developed at Idaho National Laboratory (INL) for the US Nuclear Regulatory Commission [10]. Despite it was conceived to be applied in NPPs, its use has more often been extended to other sectors [4,5,19]. Aiming to quantify HEP of workers when performing a specific task, SPARH firstly categorizes tasks as diagnosis, action or a combination of diagnosis and action. Diagnosis refers to those tasks that require the application of a cognitive process, while action include simple actions such as pressing a button [25]. Afterwards, a NHEP is associated to every task depending on the classification given (i.e. diagnosis, action or combination of diagnosis and action). To compute the final HEP, NHEP is then adjusted taking into account PSFs (Table I). In this regard, one needs to quantify only the effect of those PSFs for which sufficient information is available. Every PSF involved in the analysis is assessed by a qualitative judgment which corresponds to a multiplier. Finally, HEP is computed multiplying NHEP by PSFs multipliers. As concerns the assessment of mutual dependence between PSFs, SPARH only provides a qualitative guideline. For a more detailed description of the traditional SPARH method, the reader may refer to Gertman et al. [10].

TABLE I
PSFs OF SPARH

PSF		Description
PSF_1	Available time	Time available to complete a task
PSF_2	Stress/Stressors	Personal factors or environmental conditions that can affect worker performance
PSF_3	Complexity	Complexity of the work to be perform
PSF_4	Experience/ Training	Level of experience and knowledge regarding the task to be performed
PSF_5	Procedures	Existence of operational procedures for the tasks under consideration
PSF_6	Ergonomics/HMI	Quality of the equipment, displays and controls, layout quality, and quantity of information available from instrumentation
PSF_7	Fitness for duty	Level of mental and physical adequacy of the operator for the task under consideration
PSF_8	Work processes	Factor related to work organization, communication, management of the work team

III. DEMATEL METHOD

DEMATEL was developed at the Geneva Research Centre of the Battelle Memorial Institute by Gabus and Fontela [20] to assess the casual relationships between the evaluation criteria of a decision problem. In the present study, PSFs are considered as criteria, and DEMATEL is used to obtain both the influence degree and relative importance (i.e. the weights) of PSFs proposed by SPARH. To this purpose, pairwise comparison judgments about the mutual influence between PSFs are elicited from the Decision Maker (DM). Being C_i (with $i = 1, \ldots, n$) the i^{th} criterion (i.e. i^{th} PSF), the implementation of the method involves the following steps.

(i) Development of the direct-relation matrix Z. Using the five-point linguistic scale represented in Table II, it includes the decision maker's judgments relating to pairwise comparisons between criteria. Therefore, the generic element z_{ij} of Z represents to what extent the criterion C_i affects the criterion C_j.

TABLE II.
FIVE-POINT SCALE FOR PAIRWISE COMPARISON

Linguistic variable	Numerical value
No influence (No)	0
Very low influence (VL)	1
Low influence (L)	2
High influence (H)	3
Very high influence (VH)	4

(ii) Computation of the normalized direct-relation matrix X, where the generic element x_{ij} is computed according to the equation (1).

$$x_{ij} = \frac{z_{ij}}{\max(\sum_{j=1}^{n} z_{ij})} \quad (1)$$

(iii) Computation of the total-relation matrix T (2). Being I is the identity matrix, the generic element t_{ij} of T represents both the direct and indirect influences of the criterion C_i on the criterion C_j.

$$T = X(I-X)^{-1} \quad (2)$$

(iv) Computation of vectors (D-R) and (D+R), where the generic elements D_i and R_i are computed by the equations (3) and (4) respectively.

$$D_i = \sum_{j=1}^{n} t_{ij}, \quad \forall i = 1,2,...,n \quad (3)$$

$$R_i = \sum_{i=1}^{n} t_{ij}, \quad \forall i = 1,2,...,n \quad (4)$$

The vector (D+R) is called prominence and provides information on the relation degree of a criterion with respect to the others. The higher the value of (D+R) relating to a criterion, the higher its degree of received or provided influence. Instead, the (D-R) vector is called relation and offers information about the type of relationship between criteria. Criteria with a positive (D-R) value are defined as «net causer in the system», mainly causing effects or influences on the other criteria. On the other hand, criteria with a negative (D-R) value are defined as «net receiver in the system», mainly receiving influences by the others. As a consequence, much attention should be paid on the first group of criteria, since by improving cause factors, receiver ones are developed simultaneously [26]. In order to easily visualize the causal relationships among criteria, the two vectors may be represented on a causal diagram such as the one in Figure 1.

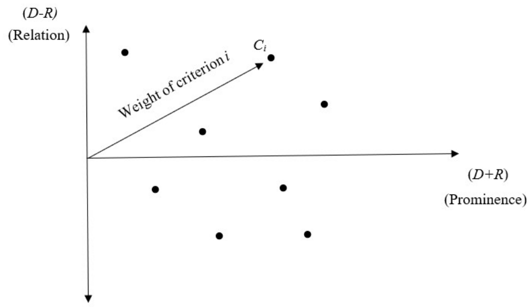

Fig. 1. Causal diagram

(v) Computation of criteria weights w_i and their normalized values q_i by the equations (5) e (6) respectively.

$$w_i = \sqrt{(D_i + R_i)^2 + (D_i - R_i)^2}, \qquad \forall i = 1,2,...,n \quad (5)$$

$$q_i = \frac{w_i}{\sum_{i=1}^{n} w_i}, \qquad \forall i = 1,2,...,n \quad (6)$$

IV. Application case

The DEMATEL-based approach is implemented in an agri-food company which produces pistachios in the Southern of Italy. The company deals with all the activities of the pistachio production chain, which also involves cultivation and harvesting. The company's owner claims the highest criticality of tasks performed by the workers at the production plant. Therefore, the assessment of the influence degree and relative importance (i.e. the weights) of PSFs focuses only on these tasks. The entire production process mainly consists of three sections, schematized in Figure 2.

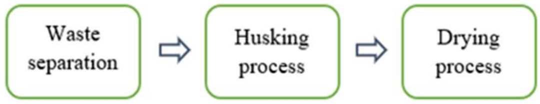

Fig. 2. Production process of pistachios

- Waste separation: once arrived at the plant, the pistachios are loaded onto a hopper and then sent through a cochlea to a gravity separator machine and to a rotary drum sorter. This way, wastes such as leaves, stones and harvest residues are removed.
- Husking process: after waste separation, pistachios are transported by a conveyor belt to a hulling machine, where they are cleaned and separated from the husk.
- Drying process: finally, pistachios are dried with streams of hot air heated by a diesel burner.

The whole process is highly automated, and operators only perform the quality check and set the process parameters. Activities related to the separation of wastes are supervised by two operators, who intervene if the pistachio flow is blocked or it is necessary to modify the process parameters (i.e. the rotation speed of the cochlea and the flow rate of the air jet of the gravity separator machine). In the husking process, the main parameters to be set are the rotation speed of the hulling machine and the flow rate of the cleaning water, which allows to take away the husk of pistachios. Finally, in the drying process, operators have to set the drying time, the temperature of the hot air and the product temperature. In particular, the product temperature must not exceed 45 °C, in order not to compromise the quality of the product and fall within the required humidity standards (i.e. 4-6 wt.%).

A. Results

Input data required by DEMATEL are obtained by the company's owner. According to Table II, the respondent is asked to express the pairwise comparison judgement between the PSFs influence, so answering the question "how much does the PSF_i affect the PSF_j?". The resulting direct-relation matrix Z is shown in Table III (see Appendix A).

After calculating the normalized direct-relation matrix through the equation (1), the total-relation matrix T (Table IV, see Appendix A) is obtained by the equation (2). Afterwards, (D+R) and (D-R) values are computed by (3) and (4) respectively, whereas PSFs weights and their normalized values are finally computed by equations (5) and (6) respectively (Table V).

The resulting causal diagram is shown in Figure 3 (see Appendix A), where "Complexity" (i.e. PSF_3) and "Work processes" (i.e. PSF_8) constitute the "net receiver in the system" group (i.e. they have a negative relation value), while "Fitness for duty" (i.e. PSF_7) and "Procedures" (i.e. PSF_5) are the only PSFs that clearly belongs to the "net causer in the system" group. The remainder PSFs (i.e. "Available time", "Experience/training", "Ergonomics/HMI", "Stress/stressors") are close to the x-axis, so that they cannot be markedly categorized into a group, namely they tend to receive and exert influences equally.

Based on DEMATEL results, the company's owner should focus primarily on improving those PSFs belonging to the "net causer in the system" group to increase the human reliability. In addition, among these factors, the ones having the highest "prominence" value have to be preferred since they play a great influence degree on the others. With this recognition, the most impactful PSF is "Procedures" with a "prominence" value equal to 14.317 and a "relation" value equal to 0.499. On the other hand, "Fitness for duty" has the highest "relation" value (i.e. 2.696), but it obtains the lowest "prominence" value (i.e. 9.473). This means that acting on the improvement of the latter PSF would be less effective for the reliability of the operator. Among PSFs with a high prominence value, "Stress/stressors" and "Ergonomics/HMI" show a high influence on "Complexity" (PSF_3), "Procedures" (PSF_5) and "Work processes" (PSF_8), as confirmed by the total-relation matrix (Table IV). Hence, minimizing any workplace stressors and providing reliable and comfortable work tools could lead to positive indirect effects on the other factors, so improving the human reliability.

TABLE V
PROMINENCE, RELATION, WEIGHTS AND NORMALIZED WEIGHTS

	(D+R)	**(D-R)**	**Weight**	**Normalized weight**
PSF_1	10.429	-0.344	10.434	0.107
PSF_2	12.710	0.113	12.711	0.130
PSF_3	13.894	-0.908	13.924	0.143
PSF_4	11.806	-0.227	11.808	0.121
PSF_5	14.317	0.499	14.326	0.147
PSF_6	12.363	0.134	12.364	0.127
PSF_7	9.473	2.696	9.850	0.101
PSF_8	11.971	-1.963	12.130	0.124

Analysing the obtained weights, PSFs have almost all the same importance degree, except for "Available time" (PSF_1) and "Fitness for duty" (PSF_7) which have lower weights than the others (i.e. 0.107 and 0.101 respectively). In fact, workers do not have to comply with strict time constraints when performing tasks as well as high levels of mental and physical efforts are not required during supervision and quality check activities. On the other hand, "Complexity" (PSF_3) and "Procedures" (PSF_5) have the highest weights (i.e. 0.143 and 0.147 respectively). In fact, the rows and columns of Table IV related to PSF_3 and PSF_5 highlight that these PSFs give and receive a high influence. As confirmed by the company's owner, the task complexity arises from the high experience and training (PSF_4) required to workers to control the products quality and/or to set the technological parameters of the whole process. For instance, properly setting the air flow of machineries used during the waste separation is a very complex task, which requires highly skilled and trained workers. The high weight of "Procedures" is justified by the high automation level of the production line. For instance, the drying process has to be performed on the basis of a specific procedure consisting of setting the drying temperature and the mixing cochlea parameters, also complying with the drying times and the products humidity. Following this procedure is necessary to ensure an excellent quality of pistachios. Another relevant PSF is "Stress/stressors" (PSF_2), having a weight equal to 0.130. As stated by the company's owner, that is due to the uncomfortable environmental conditions, characterized by a high level of noise. The computed weights could be used to assess the HEP, that actually does not represent the main focus of the present paper.

V. CONCLUSIONS

Although HRA methodologies were developed in major hazards plants (e.g. NPPs), they have been extended to other fields in recent years. The majority of these methods disregard the dependence between cognitive and personal factors (i.e. Performance Shaping Factors – PSFs) which may influence the Human Error Probability (HEP). Therefore, the paper suggests a Multi-Criteria Decision Making (MCDM) approach – based on

DEMATEL - to quantify the mutual influence and the relative importance of PSFs. The whole methodology is implemented in the agri-food sector, referring to a company which produces pistachios. Based on the comparison judgements elicited from the company's owner with relation to the performed tasks, the results show that almost all PSFs are characterized by a high level of interrelation, and "Procedures" and "Complexity" represent the most interrelated PSFs. In particular, "Procedures" is the most influencing PSF so that acting on it would have a positive effect on the other factors. A possible future line of research may concern the involvement of both more decision makers and uncertain input data in the decision making process. In addition, the proposal of some customized PSFs could be further investigated.

References

[1] French, S., Bedford, T., Pollard, S.J.T., Soane, E. (2011). Human reliability analysis: a critique and review for managers. Safety Science, 49(6), 753-763.

[2] La Fata, C.M., Giallanza, A., Micale, R., La Scalia, G., (2022). Improved FMECA for effective risk management decision making by failure modes classification under uncertainty. Engineering Failure Analysis, 2022, vol. 135, 106163.

[3] De Ambroggi, M., Trucco, P. (2011). Modelling and assessment of dependent performance shaping factors through Analytic Network Process. Reliability Engineering & System Safety, 96(7), 849-860.

[4] Aalipour, M., Ayele, Y.Z., Barabadi, A. (2016). Human reliability assessment (HRA) in maintenance of production process: a case study. International Journal of Systems Assurance Engineering and Management, 7.

[5] Burns, K., Bonaceto, C. (2020) An empirically benchmarked human reliability analysis of general aviation. Reliability Engineering & System Safety, 194.

[6] Franciosi, C., Di Pasquale, V., Iannone, R., Miranda. S. (2019). A taxonomy of performance shaping factors for human reliability analysis in industrial maintenance. Journal of Industrial Engineering and Management, 12.

[7] Swain, A.D., Guttmann, H.E. (1983). Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications. NUREG/CR-1278, US Nuclear Regulatory Commission. Washington, DC.

[8] Embrey, D.E., Humphreys, P., Rosa, E.A., Kirwan, B., Rea, K. (1984). SLIM-MADUD: an approach to assessing human error probabilities using structured expert judgment. NUREG/CR-3518. US Nuclear Regulatory Publication.

[9] Hollnagel, E. (1998). Cognitive Reliability and Error Analysis Method (CREAM). Elsevier, London.

[10] Gertman, D.I., Blackman, H.S., Marble, J.L., Smith, C., & Boring, R.L. (2005). The SPAR-H human reliability analysis method. US Nuclear Regulatory Commission.

[11] Di Pasquale, V., Miranda, S., Iannone, R., Riemma, S. (2015). A Simulator for Human Error Probability Analysis (SHERPA). Reliability Engineering & System Safety, 139, 17-32.

[12] Boring, R.L. (2010). How Many Performance Shaping Factors are Necessary for Human Reliability Analysis? US Nuclear Regulatory Commission.

[13] Park, J., Jung, W., Kim, J. (2020). Inter-relationships between performance shaping factors for human reliability analysis of nuclear power plants. Nuclear Engineering and Technology, 52(1), 87-100.

[14] Liu, J., Zou, Y., Wang, W., Zhang, L., Liu, X., Ding, Q., Qin, Z., Čepin, M. (2021). Analysis of dependencies among performance shaping factors in human reliability analysis based on a system dynamics approach. Reliability Engineering & System Safety, 215.

[15] Groth, K.M. (2009). A Data-Informed Model of Performance Shaping Factors for Use in Human Reliability Analysis. University of Maryland, College Park.

[16] Groth, K.M., Swiler; L.P. (2013). Bridging the gap between HRA research and HRA practice: a Bayesian network version of SPAR-H. Reliability Engineering & System Safety, 115, 33-42.

[17] La Fata, C.M., Giallanza, A., Micale, R., La Scalia, G., (2021a). A structured methodology for the Safety Key Performance indicator prioritization: a case study. Proceedings of 5th International Conference on System Reliability and Safety (ICSRS 2021), November 24-26th, 2021, Palermo, Italy, pp. 143-147, ISBN: 978-6654-0048-0.

[18] Kyriakidis, M., Majumdar, A., Ochieng, W.Y. (2018). The human performance railway operational index—a novel approach to assess human performance for railway operations. Reliability Engineering and System Safety, 170, pp. 226-243.

[19] La Fata, C.M., Giallanza, A., Micale, R., La Scalia, G. (2021b). Ranking of occupational health and safety risks by a multi-criteria perspective: Inclusion of human factors and application of VIKOR. Safety Science, 138.

[20] Gabus, A., Fontela, E. (1973). Perceptions of the World problematique: Communication procedure, communicating with those bearing collective responsibility. DEMATEL Report No. 1, Battelle Geneva Research Centre, Geneva, Switzerland.

[21] Dalalah, D., Hayajneh, M., Batieha, F. (2011). A fuzzy multi-criteria decision making model for supplier selection. Expert Systems with Applications, 38(7), 8384-8391.

[22] Baykasoğlu, A., Kaplanoğlu, V., Durmuşoğlu, Z.D.U., Şahin, C. (2013). Integrating fuzzy DEMATEL and fuzzy hierarchical TOPSIS methods for truck selection. Expert Systems with Applications, 40(3), 899-907.

[23] Mahmoudi, S., Jalali, A., Ahmadi, M., Abasi, P., Salari, N. (2019). Identifying critical success factors in Heart Failure Self-Care using fuzzy DEMATEL method. Applied Soft Computing, 84, 105729.

[24] Du, Y.W., Li, X.X. (2022). Critical factor identification of marine ranching ecological security with hierarchical DEMATEL. Marine Policy, 138, 104982.

[25] Whaley, A.M., Kelly, D.L., Boring, R.L., Galyean, W.J. (2012). SPAR-H Step-by-Step Guidance. Idaho National Laboratory, Idaho Falls, ID, USA.

[26] Seker, S., Zavadskas, E.K. (2017). Application of Fuzzy DEMATEL Method for Analyzing Occupational Risks on Construction Sites. Sustainability, 9, 2083. https://doi.org/10.3390/su91120

Appendix A. FIRST APPENDIX

TABLE III
DIRECT-RELATION MATRIX

	PSF_1	PSF_2	PSF_3	PSF_4	PSF_5	PSF_6	PSF_7	PSF_8
PSF_1	No	L	VH	VL	VH	H	VL	L
PSF_2	VH	No	H	VH	VH	H	VL	VH
PSF_3	VL	VH	No	VH	H	VH	H	VH
PSF_4	VL	H	VH	No	VH	H	VL	VH
PSF_5	VH	VH	VH	VH	No	VH	H	VH
PSF_6	H	H	VH	VH	VH	No	VL	H
PSF_7	H	H	VH	H	VL	VH	No	VH
PSF_8	H	H	VH	VL	VH	VL	VL	No

TABLE IV
TOTAL-RELATION MATRIX *T*

	PSF_1	PSF_2	PSF_3	PSF_4	PSF_5	PSF_6	PSF_7	PSF_8
PSF_1	0.485	0.651	0.788	0.575	0.723	0.646	0.314	0.686
PSF_2	0.725	0.666	0.897	0.776	0.854	0.754	0.368	0.878
PSF_3	0.612	0.785	0.765	0.763	0.917	0.766	0.424	0.861
PSF_4	0.567	0.706	0.845	0.578	0.776	0.688	0.337	0.807
PSF_5	0.769	0.979	0.990	0.827	0.768	0.838	0.558	0.936
PSF_6	0.674	0.755	0.905	0.763	0.831	0.632	0.361	0.828
PSF_7	0.694	0.770	0.922	0.738	0.748	0.781	0.326	0.872
PSF_8	0.565	0.626	0.750	0.540	0.689	0.549	0.299	0.576

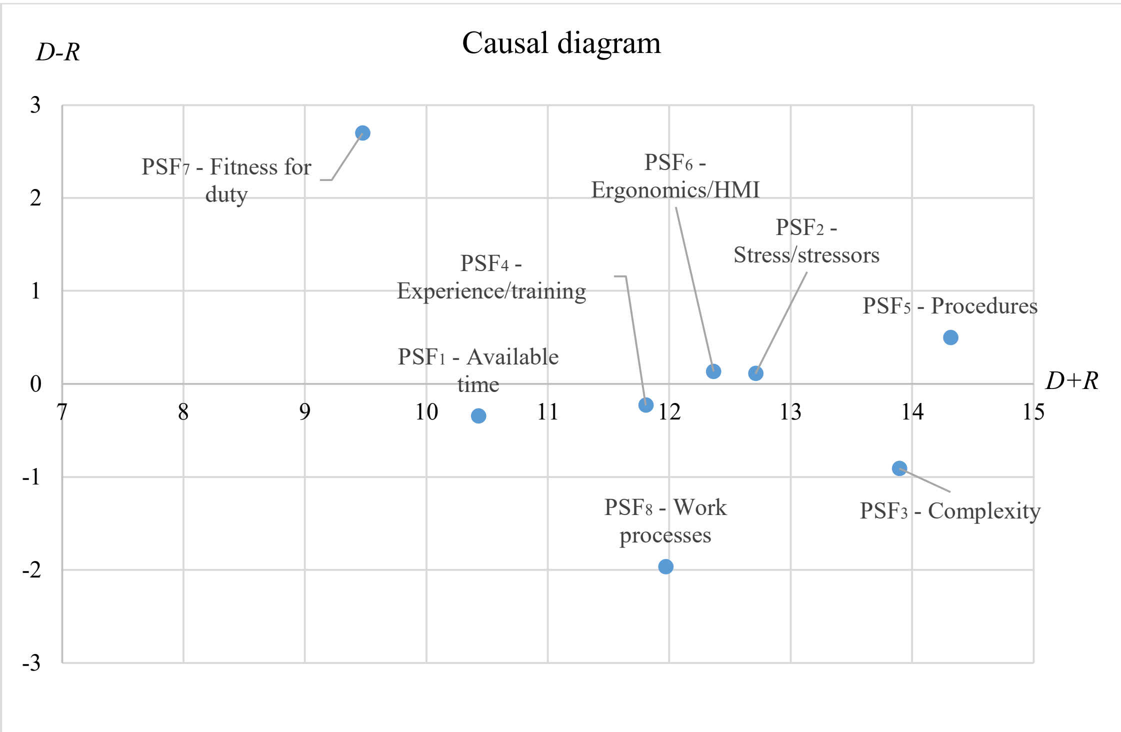

Fig. 3. Causal diagram