

THE IMPORTANCE OF DEFINING EQUIVALENT LEVELS FOR RISK ESTIMATION PARAMETERS IN THE MACHINERY RISK ASSESSMENT PROCESS

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The article focuses on the issue of risk assessment at the design stage of machinery. Risk assessment includes risk estimation and risk evaluation, based on which appropriate measures are taken. If risk estimation is performed incorrectly, this may result in the design of inadequate measures to eliminate or reduce it. There are many different risk estimation methods, but the number of studies or articles that are oriented towards comparing the results obtained by their application is significantly limited. The aim of the article is to demonstrate that the application of different risk estimation methods can indeed lead to the determination of a different risk level. Since the methods have different structures and scopes, it is necessary to define equivalent levels for the risk estimation parameters. This allows for an estimate of the risk level that corresponds to each method and subsequent analysis of the obtained results.

KEYWORDS

safety of machinery, risk assessment, risk estimation, methods, equivalent level

1 INTRODUCTION

The article focuses on the analysis of selected risk estimation methods used in the machinery design process. A helpful document in this regard is the technical report ISO/TR 14121-2:2012 concerning practical guidelines and examples of methods applicable in a specific step of machinery risk assessment. Methods based on the expression of the relationship between probability and severity/consequence of health damage are commonly applied in the risk estimation process [Pacaiova 2021].

According to Etherton [Etherton 2007], risk estimation methods allow to qualify or quantify risks, but no so-called best method can be established (many of these methods show a lot of similarity). Some companies have even developed their own analytical methods [Mauritius 2017, SICK 2026] that may not necessarily meet the needs of another company.

Charpentier [Charpentier 2003] states that the methods used in different European countries for machinery risk estimation can even lead to conflicting results, which may potentially require different levels of safety for a given machinery.

Gauthier of the Universite du Quebec a Trois-Rivieres and Chinniah of the Polytechnique Montreal have been engaged in an in-depth analysis of the methods used in industry for a long time. Under the auspices of the Institut de Recherche Robert-

Sauve en sante et en securite du travail (IRSST) based in Quebec and in collaboration with experts from the Health and Safety Laboratory (HSL) in Buxton, a study [Chinniah 2011] has been prepared which analyzes certain methods used to estimate risks in connection with industrial machinery. The implementation of this research points to the justification of using equivalent levels for the risk estimation parameters.

The aim of this paper is to compare selected machinery risk estimation methods by defining equivalent levels of their risk estimation parameters and to verify their application on a robotic manufacturing system.

2 METHODOLOGY AND METHODS

The first step is the selection and subsequent analysis of the structure and scope of the selected risk estimation methods. The next step is the definition of equivalent levels for the risk estimation parameters.

2.1 Selection and analysis of risk estimation methods

Specific methods are selected based on defined criteria listed in Tab. 1.

No.	Criterion specification
1.	Methods that comply with the recommendations of ISO/TR 14121-2:2012.
2.	Methods that are in matrix form or can be converted to this form.
3.	Methods that are popular or actually used in practice.

Table 1. Criteria used for selecting appropriate risk estimation methods

The analyzed methods are:

- Risk matrix according to ANSI B11 TR3-2000,
- Risk graph according to ISO/TR 14121-2:2012,
- Hybrid method according to ISO/TR 14121-2:2012.

Risk matrix according to ANSI B11 TR3-2000

One of the analyzed methods is the risk matrix described in the American technical report ANSI B11 TR3-2000, which is also used in European industrial practice. The Risk matrix according to ANSI B11 TR3-2000 contains two risk estimation parameters – the probability of occurrence of harm and the severity of harm. Both parameters consist of four levels, see Fig. 1. The risk levels are visualized using colour separation.

Probability of occurrence of harm (P)	Severity of harm (S)			
	Catastrophic	Serious	Moderate	Minor
Very Likely	H	H	H	M
Likely	H	H	M	L
Unlikely	M	M	L	N
Remote	L	L	N	N

Explanations: N – negligible risk, L – low risk, M – medium risk, H – high risk.

Figure 1. Risk matrix according to ANSI B11 TR3-2000

Risk can therefore be expressed as a functional dependence of two variables

$$R = f(S, P), \quad (1)$$

where R – risk of harm, f – functional dependence of variables, S – severity of harm, P – probability of occurrence of harm.

Description of the method parameters [ANSI B11 TR3-2000]

- Severity of harm (S):

Catastrophic – the result is death or such damage to health that leads to permanent disability and inability to perform work activity.

Serious – serious injury or illness that requires long-term recovery, while the person can perform work activity.

Moderate – significant injury or illness that requires medical treatment, while the person can perform the original work activity.

Minor – no or minor injury, in case of injury, first aid is sufficient without the need for temporary incapacity for work activity, or with the need for minimal time for recovery.

• Probability of occurrence of harm (P):

Very likely – health damage is almost certain.

Likely – health damage may occur.

Unlikely – health damage is not likely.

Remote – the probability of health damage is almost zero.

Risk graph according to ISO/TR 14121-2:2012

Another selected method is the risk graph in the structure presented in the technical report ISO/TR 14121-2:2012. The risk graph includes the following risk estimation parameters. The parameters severity of the injury to a person, exposure: presence of a person in the hazard zone and the possibility of avoidance considers two levels, the parameter occurrence: frequency of the hazardous event is divided into three levels. The tree structure of the Risk Graph according to ISO/TR 14121-2:2012 is illustrated in Fig. 2. The result of the risk estimation is a risk index falling into one of six levels.

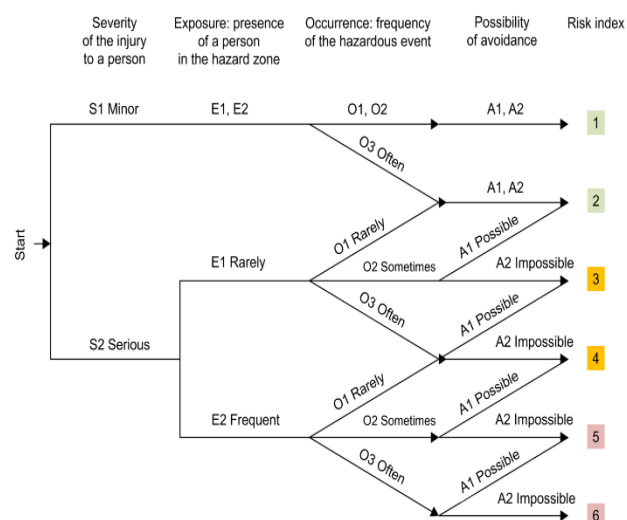


Figure 2. Risk graph according to ISO/TR 14121-2:2012

In this case, the risk is expressed by the functional dependence of the variables

$$R = f(S, E, O, A), \quad (2)$$

where R – risk of harm, f – functional dependence of variables, S – severity of the injury to a person, E – exposure: presence of a person in the hazard zone, O – occurrence: frequency of the hazardous event, A – possibility of avoidance.

Description of the method parameters [ISO/TR 14121-2:2012]:

• Severity of the injury to a person (S):

- S1 – Minor – the result is a minor reversible injury requiring first aid treatment.

- S2 – Serious – the result is a serious injury understood as irreversible or death.

• Exposure: presence of a person in the hazard zone (E):

- E1 – Rarely – the person is exposed to the hazard no more than twice per work shift, or for less than 15 minutes cumulatively during the work shift.

- E2 – Frequent – the person is exposed to the hazard more than twice per work shift, or for more than 15 minutes cumulatively during the work shift.

• Occurrence: frequency of the hazardous event (O):

- O1 – Rarely – the technology used is verified and recognized as a proven safety application.

- O2 – Sometimes – in the last two years, an event occurred in which a well-trained person with more than six months of experience in using machinery or workplace experience was exposed to health damage.

- O3 – Often – the hazardous event occurs regularly (once every six months or more often) and an untrained person with less than six months of experience in the workplace is exposed to health damage, or a person's health damage has occurred in connection with the given hazardous event in the previous ten years.

• Possibility of avoidance (A):

- A1 – Possible – possible if it is a well-trained person aware of the risk who has sufficient time to prevent health damage (for example, the speed of moving parts is less than 0.25 m·s⁻¹) or if it is possible to prevent health damage by adjusting specific working conditions (factors of the working environment or the way in which the work activity is performed).

- A2 – Impossible.

Hybrid method according to ISO/TR 14121-2:2012

Hybrid method according to ISO/TR 14121-2:2012 considers similar parameters as the Risk graph method according to ISO/TR 14121-2:2012. The risk is expressed as a functional dependence of two variables

$$R = f(Se, CI), \quad (3)$$

where R – risk of harm, f – functional dependence of variables, Se – severity of injury, CI – calculate class.

The probability of occurrence of harm is determined through the so-called category CI from the relationship

$$CI = Fr + Pr + Av, \quad (4)$$

where Fr – frequency of exposure, Pr – probability of occurrence, Av – Avoidability.

Fig. 3 shows three parameters of risk estimation. The frequency of exposure to the hazard and the probability of the occurrence are divided into five levels, the avoidability into three levels.

Category CI				
Frequency of exposure (Fr)		Probability of occurrence (Pr)	Avoidability (Av)	
< 1 h	5	Very high	5	
> 1 h < 24 h	5	Probable	4	
> 24 h < 2 weeks	4	Possible	3	Impossible 5
> 2 weeks < 1 year	3	Rare	2	Possible 3
> 1 year	2	Negligible	1	Probable 1

Figure 3. Hybrid method according to ISO/TR 14121-2:2012 – numerical scoring of the CI category (probability of occurrence of harm) using three auxiliary parameters

Fig. 4 characterizes four levels of the fourth parameter for risk estimation – severity of injury and gives rise to three possible levels of risk.

Description of the method parameters [ISO/TR 14121-2:2012]:

• Severity of injury (Se):

- 1 – in the event of an injury, first aid is sufficient.

- 2 – the injury requires medical treatment.
- 3 – the injury is understood as irreversible and after recovery leads to minor problems for the person to perform the work activity.
- 4 – the injury is understood as irreversible and after recovery leads to serious problems for the person to the point of inability to perform the work activity.
- Frequency of exposure (Fr):
- 2 – the person is exposed to risk over a period of more than one year.
- 3 – the person is exposed to risk over a period of two weeks to one year.
- 4 – the person is exposed to risk over a period of more than one day to two weeks.
- 5 – the person is exposed to risk over a period of more than one hour to one day.
- 5 – the person is exposed to risk over a period of one hour or less.
- Probability of occurrence (Pr):
- 1 – *Negligible* – the part of the equipment will never fail to cause a hazardous event, and human error is not possible.
- 2 – *Rare* – the part of the equipment is unlikely to fail to cause a hazardous event and human error is unlikely.
- 3 – *Possible* – the part of the equipment may fail to cause a hazardous event and human error is possible.
- 4 – *Probable* – the part of the equipment is likely to fail to cause a hazardous event and human error is likely.
- 5 – *Very high* – the part is not suitable for the application, fails and causes a hazardous event, the probability of human error is very high.
- Avoidability (Av):
- 1 – *Probable* – if the protection fails, the occurrence of a hazardous event will be largely prevented.
- 3 – *Possible* – if exposed to a hazard, it is possible to react in time and avoid damage to health.
- 5 – *Impossible* – it is not possible to react in time and avoid damage to health.

Consequences	Severity of injury (Se)	Category CI				
		3-4	5-7	8-10	11-13	14-15
Fatality, permanently debilitating injury or illness, that is involving the loss of an organ and therefore its function	4	M	H	H	H	H
Seriously debilitating injury or illness, that is involving the weakening of an organ and therefore its function	3	L	M	H	H	H
Injury or significant disease requiring specialized medical treatment	2	L	L	M	H	H
Injuries or minor injuries requiring first aid (no loss of working days)	1	L	L	L	M	H

Explanations: L – low risk, M – medium risk, H – high risk.

Figure 4. Hybrid method according to ISO/TR 14121-2:2012 – parameter severity of injury and risk levels

An overall overview of applied parameters and number of parameter levels is shown in Fig. 5 (note: the parameter exposure: presence of a person in the hazard zone used in Risk graph according to ISO/TR 14121-2:2012 includes two parameters – frequency of exposure and duration of exposure).

Parameter	Number of parameter levels for each method		
	Risk matrix according to ANSI B11 TR3-2000	Risk graph according to ISO/TR 14121-2:2012	Hybrid method according to ISO/TR 14121-2:2012
Severity	4	2	4
Probability of occurrence of harm	4	-	-
Frequency of exposure	-	2	5
Duration of exposure	-	2	-
Probability of occurrence	-	3	5
Possibility of avoidance	-	2	3

Explanations: - A sign that a given parameter does not occur in a given method.

Figure 5. Parameters and number of parameter levels of the analyzed methods

The overview of risk levels is presented in Fig. 6.

Parameter	Number of risk levels		
	Risk matrix according to ANSI B11 TR3-2000	Risk graph according to ISO/TR 14121-2:2012	Hybrid method according to ISO/TR 14121-2:2012
Risk	4	6	3

Figure 6. Number of risk levels of analyzed methods

2.2 Definition of equivalent levels for the risk estimation parameters

The results of methods with different structures and scopes can be compared by assigning equivalent levels to the individual risk estimation parameters of each analyzed method. The reason for establishing equivalent levels for risk estimation parameters is not only the diversity of the parameters used and the difference in the number of their levels, but also the inconsistent way of defining these levels. This can lead to different and erroneous interpretations of important concepts. The basis for defining equivalent levels is the knowledge obtained from the analysis of the IRSST/HSL research study [Chinniah 2011, Chinniah 2018] and selected methods.

Equivalent levels of the severity parameter

When examining the structure of the selected methods, it can be noted that the severity parameter considers several factors, depending on the method.

The Risk matrix according to ANSI B11 TR3-2000 considers the degree of treatment required, the time needed for recovery, and the ability to return to work activity. No injury is ranked at the same level as an injury that may require minimal recovery time (*Minor*), or permanent disability is ranked at the same level as death (*Catastrophic*).

The Risk graph according to ISO/TR 14121-2:2012 defines the severity levels according to the reversibility of the injury and the need for first aid. Since the method considers only two levels of this parameter, this is a very broad generalization. It is helpful to give examples of possible injuries. From which all fractures are understood as serious irreversible injuries and, together with, for example, the loss of part of a finger, are ranked on the same level of severity as death.

The Hybrid method according to ISO/TR 14121-2:2012 considers the degree of necessary treatment, the reversibility of the injury and the ability to perform work activity after recovery. However, the possibility of death is completely absent.

To cover the diversity of definitions, due to the consideration of different factors, and to eliminate the inconsistency of

parameter levels in individual methods, the following equivalent levels (S_{eq}) are considered:

- S_{eq1} – minor injuries not requiring first aid (bruises, minor cuts).
- S_{eq2} – minor injuries requiring first aid without the need for temporary incapacity for work (superficial burns, eye irritation).
- S_{eq3} – injuries requiring medical treatment with the need for follow-up treatment (deep cuts, minor fractures, burns).
- S_{eq4} – injuries leading to irreversible damage to health, while the person can perform the original work activity (loss of part of a finger).
- S_{eq5} – serious injuries leading to the person's inability to perform the original work activity (extensive fractures, loss of an eye).
- S_{eq6} – serious injuries leading to permanent disability and inability to perform the work activity (loss of a limb).
- S_{eq7} – death of one person.
- S_{eq8} – death of several people.

The conversion of the severity parameter levels of each analyzed method into equivalent levels is shown in Fig. 7.

Method	Equivalent level of the severity parameter (S_{eq})							
	S_{eq1}	S_{eq2}	S_{eq3}	S_{eq4}	S_{eq5}	S_{eq6}	S_{eq7}	S_{eq8}
Risk matrix according to ANSI B11 TR3-2000	Minor		Moderate	Serious		Catastrophic		
Risk graph according to ISO/TR 14121-2:2012	S1 - Minor		S2 - Serious					
Hybrid method according to ISO/TR 14121-2:2012	1		2	3	4			

Explanations: The colour distinction has no specific meaning, it is implemented only for the purpose of better readability of the data.

Figure 7. Equivalent level of the severity parameter

Equivalent levels of the probability of occurrence parameter

The probability of occurrence of harm parameter is used only in the Risk matrix according to ANSI B11 TR3-2000.

Experience gained from the use of methods that consider the probability of occurrence of harm parameter shows that at least three levels of the parameter are considered [Gauthier 2012]. In general, it is more difficult to determine the probability level than the severity level. This is due to the ambiguity of the definitions of the parameter levels and the different ways of their gradation depending on the method.

After taking into account the above facts, it is possible to apply equivalent levels (P_{eq}) for the probability of occurrence of harm parameter:

- P_{eq1} – almost impossible occurrence.
- P_{eq2} – unlikely occurrence, but possible.
- P_{eq3} – possible occurrence, but not expected.
- P_{eq4} – possible occurrence, expected.
- P_{eq5} – almost certain occurrence, will occur at least once.
- P_{eq6} – will occur more than once.
- P_{eq7} – occurs frequently (even regularly).

The relationship between the equivalent levels of the probability of occurrence of harm parameter and the corresponding levels of the given method are presented in Fig. 8.

The probability of occurrence (of a hazardous event) parameter is considered by the two analyzed methods.

The Risk graph according to ISO/TR 14121-2:2012 focuses on the reliability of the applied safety technology, the awareness and

experience of the person operating the machinery, the history of hazardous events and accident statistics.

Method	Equivalent level of the probability of occurrence of harm parameter (P_{eq})						
	P_{eq1}	P_{eq2}	P_{eq3}	P_{eq4}	P_{eq5}	P_{eq6}	P_{eq7}
Risk matrix according to ANSI B11 TR3-2000	Remote	Unlikely		Likely	Very likely		

Explanations: The colour distinction has no specific meaning, it is implemented only for the purpose of better readability of the data.

Figure 8. Equivalent level of the probability of occurrence of harm parameter

The Hybrid method according to ISO/TR 14121-2:2012 determines the possible level of the parameter using the probability of failure of a part of the equipment and the possibility of human error.

When determining the equivalent levels of the probability of occurrence (of a hazardous event), it is possible to proceed from the fact that the levels used in the Hybrid method according to ISO/TR 14121-2:2012 essentially cover all possibilities. The equivalent levels are therefore as follows (O_{eq}):

- O_{eq1} – negligible.
- O_{eq2} – rare.
- O_{eq3} – possible.
- O_{eq4} – probable.
- O_{eq5} – very high.

The conversion of the levels of the probability of occurrence (of a hazardous event) parameter into equivalent levels is shown in Fig. 9.

Method	Equivalent level of the probability of occurrence (of hazardous event) parameter (O_{eq})				
	O_{eq1}	O_{eq2}	O_{eq3}	O_{eq4}	O_{eq5}
Risk graph according to ISO/TR 14121-2:2012	O1 - Rarely		O2 - Sometimes	O3 - Often	
Hybrid method according to ISO/TR 14121-2:2012	1 - Negligible	2 - Rare	3 - Possible	4 - Probable	5 - Very high

Explanations: The colour distinction has no specific meaning, it is implemented only for the purpose of better readability of the data.

Figure 9. Equivalent level of the probability of occurrence (of hazardous event) parameter

Equivalent levels of the frequency of exposure parameter

The Risk graph method according to ISO/TR 14121-2:2012 uses the number of possible incidents per work shift to determine the level of frequency of exposure to a hazard.

The Hybrid method according to ISO/TR 14121-2:2012 focuses on the average intervals between exposures to a hazard and not on the number of repetitions.

To unify the levels used for the parameter in the individual methods, equivalent levels (F_{eq}) of the type are used:

- F_{eq1} – a person is exposed to the hazard once in a period longer than a year.
- F_{eq2} – a person is exposed to the hazard once in a year.
- F_{eq3} – a person is exposed to the hazard once in a month.
- F_{eq4} – a person is exposed to the hazard once in a week.
- F_{eq5} – a person is exposed to the hazard once or twice a day.
- F_{eq6} – a person is exposed to the hazard twice a day to once in two hours.
- F_{eq7} – a person is exposed to the hazard once in two hours to once in an hour.
- F_{eq8} – a person is exposed to the hazard several times an hour or continuously.

The coverage of equivalent levels of the frequency of exposure (to a hazard) parameter is presented in Fig. 10.

Method	Equivalent level of the frequency of exposure (to a hazard) parameter (F_{eq})							
	F_{eq1}	F_{eq2}	F_{eq3}	F_{eq4}	F_{eq5}	F_{eq6}	F_{eq7}	F_{eq8}
Risk graph according to ISO/TR 14121-2:2012	E1 - Rarely					E2 - Frequent		
Hybrid method according to ISO/TR 14121-2:2012	2	3	4	5	5			

Explanations: The colour distinction has no specific meaning, it is implemented only for the purpose of better readability of the data.

Figure 10. Equivalent level of the frequency of exposure (to a hazard) parameter

Equivalent levels of the duration of exposure parameter

The duration of exposure (to a hazard) parameter occurs in the Risk graph method according to ISO/TR 14121-2:2012. The method considers the cumulative duration of exposure to the hazard per work shift.

It is also important to note the Hybrid method according to ISO/TR 14121-2:2012, which mentions the duration of exposure to the hazard. However, this only states that it is possible to determine a lower level of the frequency of exposure parameter if the duration of exposure to the hazard is shorter than 10 minutes. However, it does not specifically address the parameter in question.

The following equivalent levels (D_{eq}) are defined for the parameter duration of exposure to the hazard:

- D_{eq1} – the person is exposed to the hazard for a very short time, maximum 1/30 of the work shift.
- D_{eq2} – the person is exposed to the hazard for a short to longer time, maximum 1/10 of the work shift.
- D_{eq3} – the person is exposed to the hazard for a maximum of 1/5 of the work shift.
- D_{eq4} – the person is exposed to the hazard for half of the work shift.
- D_{eq5} – the person is exposed to the hazard continuously during the work shift.

The relationship between the equivalent levels of the duration of exposure (to a hazard) parameter and the levels of the Risk graph according to ISO/TR 14121-2:2012 is shown in Fig. 11.

Method	Equivalent level of the duration of exposure (to a hazard) parameter (D_{eq})				
	D_{eq1}	D_{eq2}	D_{eq3}	D_{eq4}	D_{eq5}
Risk graph according to ISO/TR 14121-2:2012	E1 - Rarely		E2 - Frequent		

Explanations: The colour distinction has no specific meaning, it is implemented only for the purpose of better readability of the data.

Figure 11. Equivalent level of the duration of exposure (to a hazard) parameter

Equivalent levels of the possibility of avoidance parameter

The last parameter to focus on is the possibility of preventing or limiting damage to health.

The Risk graph according to ISO/TR 14121-2:2012 uses factors such as the person's awareness, the possible reaction time to the hazard and other factors that eliminate damage to the person's health to decide on the appropriate parameter level.

The Hybrid method according to ISO/TR 14121-2:2012 describes the individual parameter levels using specific examples. In general, it can be summarized that it focuses on the design of the machinery and the possible reaction time to the hazard.

Based on the analysis of the parameter levels in individual methods, equivalent levels (A_{eq}) are defined:

- A_{eq1} – simple.
- A_{eq2} – probable.
- A_{eq3} – possible.
- A_{eq4} – possible under certain conditions (practically possible).
- A_{eq5} – improbable.
- A_{eq6} – impossible.

The dependence of the equivalent levels of the possibility of avoidance damage to health parameter on the levels used in the individual analyzed methods is presented in Fig. 12.

Method	Equivalent level of the possibility of avoidance (damage to a health) parameter (A_{eq})					
	A_{eq1}	A_{eq2}	A_{eq3}	A_{eq4}	A_{eq5}	A_{eq6}
Risk graph according to ISO/TR 14121-2:2012	A1 - Possible					A2 - Impossible
Hybrid method according to ISO/TR 14121-2:2012	1 - Probable	3 - Possible			5 - Impossible	

Explanations: The colour distinction has no specific meaning, it is implemented only for the purpose of better readability of the data.

Figure 12. Equivalent level of the possibility of avoidance (damage to health) parameter

3 PRACTICAL APPLICATION

The object of risk assessment is a manufacturing system for automatic cutting of drawn aluminum profiles, robotic handling and palletizing of the cut semi-finished product, see Fig. 13.

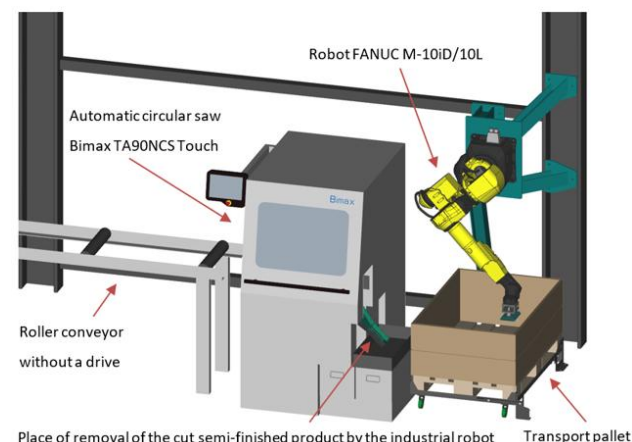


Figure 13. Structure of the assessed robotic manufacturing system

After starting the work cycle, the primary input material is moved along the roller conveyor to the circular saw. The material is moved for the cutting operation by a feed mechanism located in the working area of the circular saw. The cut semi-finished product is moved by a slip to the removal point by a traditional industrial articulated robot. The robot with a vacuum end effector removes the semi-finished product, Fig. 14, and then places it on a transport pallet, Fig. 15. The operator's tasks are to ensure the supply of primary input material (placing the primary input material on the roller conveyor and inserting part of it into the circular saw), to control the progress of the automated manufacturing process and to replace the transport pallet after it is filled [Bozek 2021, Zidek 2024].

Based on the risk assessment, appropriate elimination or reduction measures have been taken, such as [Sagova 2025]:

- Edge modification of the anchor structure and the effector.
- Verification of the anchor structure in terms of limit state under static and dynamic stress.

- Three-position activation switch in the Teach pendant.
- Dedication of the zone for safe movement of the robot (using FANUC Dual Check Safety (DCS) software option).
- Preventing access to the hazard zone (certified fixed and movable polycarbonate covers).
- The door fitted with a safety lock with an interlocking device, securing the closed position of the door during operation and an internal panic handle.
- Dual-channel connection to prevent unexpected restart of the robotic device.
- Validation of the reliability of the safety-related parts of the control system.
- Informing about residual risks (safety warnings).
- Training of operators about the possible risk.
- Adhering to inspection intervals and performing regular maintenance (electrical parts, safety parts and others).

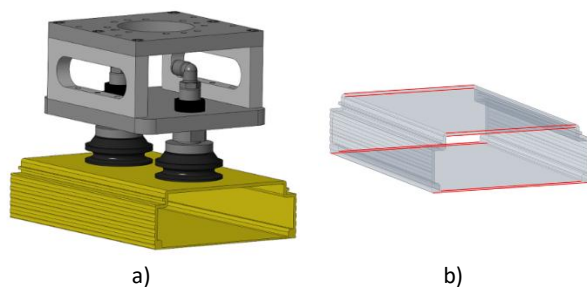


Figure 14. Visualization of the handling object: a) method of gripping the object; b) representation of edges for deburring

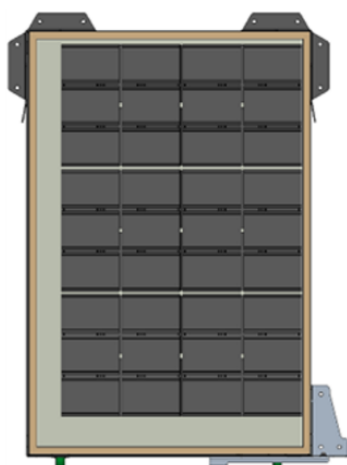


Figure 15. Transport pallet with handling objects (floor plan)

The operator enters the hazardous zone in normal operation during the work shift twice to change the pallet and twice to clean the work area (when changing the pallet, in the middle and at the end of the work shift). The networking time is 8 hours a day. Each time a full pallet is replaced with an empty one, the operator is within the robot's reach for a total of 2 minutes, and during daily cleaning it is up to 15 minutes. In addition, he also performs weekly cleaning and maintenance aimed at removing settled dirt and checking and eliminating compressed air leaks. The duration of weekly maintenance affects the result of the inspection. However, it is at least 10 minutes. The identified hazards are listed in Table 2.

After identifying the hazards, an estimate of the risk level is made using defined equivalent levels for individual risk estimation parameters. As an example, the determination of the level of the severity parameter by assigning the equivalent level S_{eq4} – injuries leading to irreversible damage to health, while the person can perform the original work activity (loss of part of a finger).

No.*	Type or group	Origin*
1	Mechanical hazards	1.2 Angular parts 1.3 Approach of a moving element to a fixed part 1.6 Falling objects 1.12 Machinery mobility 1.16 Sharp edges 1.17 Stored energy
2	Electrical hazards	2.4 Live parts 2.7 Parts which have become live under fault conditions
4	Noise hazards	4.8 Whistling pneumatics 4.9 Worn parts
7	Material/substance hazards	7.8 Fluid 7.10 Gas
8	Ergonomic hazards	8.1 Access 8.3 Design, location or identification of control devices 8.4 Effort 8.6 Local lighting 8.9 Repetitive activity
9	Hazards associated with the environment in which the machine is used	9.5 Pollution 9.11 Elevated parts of the structure
10	Combination of hazards	10.1 Operator error 10.2 Robot control 10.3 Defined safety function failure 10.4 Stuck in the work-space of a robotic cell

Table 2. Identified hazards

*Explanatory note: The numbering of individual types or groups of hazards and origins corresponds to the order given in the relevant standards [ISO 12100:2010, ISO 10218-2:2025].

If the equivalent level S_{eq4} is selected in the risk estimation process, given the definitions of the levels of this parameter in the individual methods, the corresponding level is the level shown in Fig. 16, see red border. The above logic must be applied when determining the level of each parameter of the method.

Method	Equivalent level of the severity parameter (S_{eq})							
	S_{eq1}	S_{eq2}	S_{eq3}	S_{eq4}	S_{eq5}	S_{eq6}	S_{eq7}	S_{eq8}
Risk matrix according to ANSI B11 TR3-2000	Minor		Moderate	Serious	Catastrophic			
Risk graph according to ISO/TR 14121-2:2012	S1 - Minor				S2 - Serious			
Hybrid method according to ISO/TR 14121-2:2012	1	2	3	4				

Explanations. The colour distinction has no specific meaning, it is implemented only for the purpose of better readability of the data.

Figure 16. Determination of the level of the severity parameter using equivalent levels

The risk estimation performed for each identified hazard by successive application of the individual analyzed methods is presented in Fig. 17. The colour distinction visualizes the achieved level of risk defined by the specific method. The symbols used are based on the concepts shown in Fig. 1- Fig. 4.

No.*	Method													
	Risk matrix according to ANSI B11 TR3-2000			Risk graf according to ISO/TR 14121-2:2012					Hybrid method according to ISO/TR 14121-2:2012					
	S	P	R	S	F	O	A	R	Se	Fr	Pr	Av	R	
1.2	Mi	VL	Me	1	2	2	2	1	1	5	3	5	Me	
1.3	C	U	Me	2	2	1	1	3	4	5	1	1	H	
1.6	S	L	H	2	2	1	2	4	4	5	1	5	H	
1.12	S	U	Me	2	2	1	1	3	4	5	1	1	H	
1.16	Mi	U	N	1	2	1	1	1	1	5	1	1	L	
1.17	C	U	Me	2	1	1	1	2	4	3	1	1	H	
2.4	C	U	Me	2	2	1	1	3	4	5	1	1	H	
2.7	C	U	Me	2	2	1	1	3	4	5	1	1	H	
4.8	Mi	U	N	1	2	1	1	1	1	5	2	3	L	
4.9	Mi	U	N	1	2	1	1	1	1	5	2	3	L	
7.8	Mi	U	N	1	2	2	1	1	1	5	3	1	L	
7.10	Mo	U	L	2	1	1	1	2	2	3	1	1	L	
8.1	Mi	R	N	1	2	1	1	1	1	5	1	1	L	
8.3	Mi	R	N	1	2	1	1	1	1	5	1	1	L	
8.4	Mi	VL	Me	1	2	2	2	1	1	5	3	5	Me	
8.6	Mi	U	N	1	2	1	1	1	1	5	2	1	L	
8.9	Mi	VL	Me	1	2	2	2	1	1	5	3	5	Me	
9.5	Mi	L	L	1	2	3	1	2	1	5	5	1	Me	
9.11	Mi	VL	Me	1	2	2	2	1	1	5	3	5	Me	
10.1	S	U	Me	2	2	1	1	3	3	5	2	3	H	
10.2	S	U	Me	2	2	1	1	3	3	5	2	1	H	
10.3	C	U	Me	2	2	1	1	3	4	5	1	3	H	
10.4	C	U	Me	2	2	1	1	3	4	5	1	1	H	

*Explanatory note: The numbering of individual origins corresponds to the order given in Table 2.

Figure 17. The risk estimation of identified hazards using analyzed methods

4 DISCUSSION

Three methods are analyzed in the paper, one two-parameter method (Risk matrix according to ANSI B11 TR3-2000) and two four-parameter methods (Risk graph according to ISO/TR 14121-2:2012, Hybrid method according to ISO/TR 14121-2:2012). The definitions of parameter levels consider, depending on the method, different factors that are intended to help estimate their level and/or different gradations. The basis for assigning an equivalent level to individual parameters is a thorough analysis of the risk estimation methods that are subjected to research. Defining equivalent levels for risk estimation parameters allows to determine whether there is a difference between the results obtained using different methods. The purpose of such an analysis is to verify how effectively and reliably the level of risk can be determined using individual methods, which is the basis for the decision-making process on the need to propose measures to eliminate or reduce the risk arising from the relevant threat, or to set priorities for taking appropriate measures.

Based on the risk estimation performed using the selected methods and the analysis of the results, it can be stated: The analyzed risk estimation methods show results that really differ from each other for certain types of hazards, see Fig. 17. This fact visibly occurs when determining the combination of parameter levels of individual methods, as in the case of hazard

1.17 – Stored energy. On the one hand, the Risk graph method according to ISO/TR 14121-2:2012 determines a low level of risk (2) and on the other hand, the Hybrid method according to ISO/TR 14121-2:2012 determines the maximum level of risk of health damage (H). The results of risk estimation for hazards 1.2 – Angular parts, 8.4 – Effort, 8.9 – Repetitive activity, 9.5 – Pollution or 9.11 – Elevated parts of the structure, where a minimum to medium level of risk is considered, cannot be omitted. Or, from the opposite point of view, for hazards 1.3 – Approach of a moving part to a fixed part, 1.12 – Machine mobility, electrical hazards and combined hazards, where a medium to maximum level of risk is determined.

The logical fact is that uncertainty is a natural part of the risk estimation and some difference in the results of the methods used is tolerable. However, specific guidelines will help to improve this process. Therefore, it is appropriate to compile a set of recommendations for the selection, development of new, or optimization of existing methods that do not overestimate or underestimate the resulting risk level of health damage.

5 CONCLUSIONS

Without a responsible approach to risk assessment, it is difficult to make decisions about the appropriate type of measure to eliminate or reduce the risk of machinery. Specialists tasked with carrying out machinery risk assessments are confronted with a variety of methods designed to estimate and evaluate risk.

There are various types of research and publications that highlight the benefits of a properly conducted risk assessment process. However, at a minimum, one can encounter research that directly focuses on the risk assessment process and reveals shortcomings in the methods used that can lead to incorrect risk estimates [Gauthier 2018, Chinniah 2018].

Equivalent levels are the basis for the possibility of comparing results obtained by applying methods with different structures, different numbers of parameter levels and different definitions of these levels. At the same time, the advantage of using equivalent levels is to minimize the subjective judgments of those performing the risk assessment. After the risk estimation has been carried out by defining equivalent levels for the risk estimation parameters, it is also necessary to define equivalent levels for the estimated risk itself. Without determining an equivalent level for the estimated risk, it is not possible to perform a statistical analysis of the obtained results.

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