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RISK EVALUATION OF ADDITIVE MANUFACTURING TECHNOLOGIES IN AUTOMOTIVE INDUSTRY USING THE KINNEY METHOD

PROCENA RIZIKA TEHNOLOGIJA ADITIVNE PROIZVODNJE U AUTOMOBILSKOJ INDUSTRIJI PRIMENOM KINI METODE

Originalni naučni rad / Original scientific paper
Rad primljen / Paper received: 15.07.2025
https://doi.org/10.69644//ivk-2025-03-0405

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Keywords
- additive manufacturing
- automotive industry
- risk assessment
- Kinney method
- protective measures

Abstract

Additive Manufacturing (AM) technologies have fundamentally transformed production workflows across numerous industries, with especially profound effects in the automotive industry. By enabling the creation of complex, lightweight, and highly customised components that are difficult or even impossible to achieve through traditional manufacturing methods, AM significantly accelerates prototyping, shortens product development cycles, and fosters innovative vehicle design. However, the impact of AM on worker health and safety remains inadequately explored, particularly given the wide range of materials and energy sources involved in these processes. This research utilises the Kinney risk assessment method to systematically quantify the hazards associated with various AM technologies employed in automotive industry. Drawing from these insights, the paper proposes targeted protective strategies designed to safeguard workers while preserving the productivity and innovative advantages that AM delivers to the automotive industry.

Ključne reči
- aditivna proizvodnja
- automobilska industrija
- procena rizika
- Kini metoda
- zaštitne mere

Izvod

Tehnologije aditivne proizvodne su fundamentalno transformisale tokove proizvodnje u brojnim industrijama, a naročito u automobilskoj. Omogućavajući kreiranje složenih, laganih i visoko prilagođenih komponenata koje je teško ili čak nemoguće postići tradicionalnim metodama proizvodnje, aditivna proizvodnja značajno ubrzava prototipizaciju, skraćuje cikluse razvoja proizvoda i podstiče inovativan dizajn vozila. Međutim, uticaj aditivne proizvodnje na zdravlje i bezbednost radnika je neadekvatno istražen, posebno imajući u vidu širok spektar materijala i izvora energije koji se koriste u ovim procesima. U ovom istraživanju primenjena je Kini metoda procene rizika za sistematsko kvantifikovanje opasnosti u različitim tehnologijama aditivne proizvodnje koje se primenjuju u automobilskoj industriji. Na osnovu rezultata ovog istraživanja, u ovom radu predložene su strategije u cilju zaštite radnika, istovremeno čuvajući produktivnost i inovativne prednosti koje aditivna proizvodnja donosi automobilskoj industriji.

INTRODUCTION

Workplace safety and health protection are foundational to the sustainable growth and operational success of modern industries, especially in automotive industry where cutting-edge technologies like Additive Manufacturing (AM) are becoming integral to production lines. The automotive industry increasingly relies on AM to produce complex, lightweight, and highly customised components, pushing the boundaries of vehicle design and performance. However, integrating AM introduces new occupational hazards that must be managed carefully to protect workers and ensure uninterrupted manufacturing processes.

A safe working environment directly reduces occupational injuries, illnesses, and accidents, which in turn boosts productivity, enhances employee morale, and maintains operational continuity - critical factors for automotive manufacturers competing in a fast-paced global market /1/. Beyond protecting the workforce, cultivating a robust safety culture helps companies avoid costly legal liabilities and regulatory penalties, while strengthening their reputation as responsible employers and innovative industry leaders. Strategic investments in occupational health and safety also translate into reduced absenteeism and lower insurance costs, offering automotive companies a tangible competitive advantage.

Over the past three decades, AM technologies have evolved from niche applications into mainstream industrial tools, with their reach extending into educational and consumer sectors as well. Within automotive industry, AM enables rapid prototyping, flexible customisation of parts, and production of components with intricate geometries, optimised lightweight structures, and enhanced functional performance. The widespread availability of technical documentation, extensive digital 3D model libraries, and practical case studies has accelerated AM adoption throughout the industry.

Many studies focus on appropriate characterisation of material properties used for AM indicating the limitation in their application /2-4/, but despite these advancements, the health and safety risks inherent in AM processes remain insufficiently explored. Potential hazards include exposure to fine and ultrafine particles released from metal powders and polymer resins, chemical risks from volatile compounds, and thermal or radiation dangers associated with energy-intensive AM equipment. Notably, scientific research and safety guidelines lag behind technological progress, with far fewer studies addressing occupational health concerns compared to those focusing on AM innovation. The analysis of expert literature also indicates that significant efforts are being made to improve AM technologies /5/, while the safety aspects of these technologies remain underexplored.

This gap highlights the need for comprehensive risk assessments and proactive safety strategies tailored to automotive AM environments.

ADDITIVE MANUFACTURING TECHNOLOGIES IN AUTOMOTIVE INDUSTRY

According to the ASTM ISO/ASTM 52900-21 standard /6/, AM technologies are categorised into seven main groups, each playing a significant role in various stages of automotive design and production:

Vat Photopolymerisation: this process involves selectively curing liquid photopolymers using light, allowing for the creation of high-resolution prototypes and precision tooling moulds. Stereolithography (SLA) is a widely used technology in this category. Automotive manufacturers use vat photopolymerisation for producing detailed concept models, functional prototypes, and master patterns for casting, helping accelerate design validation and tooling development.

Material Jetting: by depositing droplets of material layer by layer, material jetting enables the production of multi-material or multi-colour parts. This capability is particularly valuable for visual prototypes, aesthetic concept models, and simulation parts where realistic surface finishes and varied material properties are needed. Automotive designers leverage this to communicate design intent clearly and to refine ergonomics and styling before committing to mass production.

Binder Jetting: this technology employs liquid binders to selectively join powdered materials. It is instrumental in producing metal parts rapidly, often used for functional testing, small-batch production, and complex geometries that would be difficult to machine conventionally. In automotive industry, binder jetting helps reduce lead times for prototype metal components and supports customised part production, such as bespoke suspension or drivetrain elements.

Powder Bed Fusion: arguably the most impactful AM technology for automotive applications, powder bed fusion uses thermal energy - commonly via lasers or electron beams - to selectively melt and fuse metal powders. Techniques like Selective Laser Melting (SLM) and Electron Beam Melting (EBM) produce lightweight, highly durable parts that meet stringent mechanical requirements. Automotive uses include engine components, lightweight structural elements, and safety-critical parts, where performance and weight reduction directly contribute to vehicle efficiency and emissions reduction.

Material Extrusion: this process involves pushing material through a nozzle to build parts layer by layer. It is primarily used for prototyping, creating fixtures, jigs, and tooling aids within automotive industry workflows. Material Extrusion offers cost-effective, rapid fabrication of custom aids that improve assembly precision and reduce production downtime.

Directed Energy Deposition: utilising focused thermal energy to fuse deposited material, this technology supports part repair, hybrid manufacturing, and adding material to existing components. In the automotive industry, it extends the lifecycle of expensive parts by enabling on-site repairs, facilitates design modifications during production, and supports the manufacture of complex components that blend additive and subtractive techniques.

Sheet Lamination: this method bonds sheets of material sequentially to form objects, with potential applications in producing layered metal parts for lightweight vehicle structures. Although less common, sheet lamination offers promising avenues for manufacturing complex assemblies with tailored mechanical properties, potentially reducing part count and simplifying vehicle architecture.

Together, these diverse AM technologies empower automotive manufacturers to push boundaries in design and production efficiency. They contribute significantly to reducing vehicle weight - which directly improves fuel economy and lowers emissions - and enable rapid innovation cycles.

However, the variety of materials used (metals, polymers, composites) and the energies involved (lasers, electron beams, ultraviolet light) introduce distinct occupational hazards. These range from exposure to fine and ultrafine particles, chemical vapours, and toxic powders to thermal burns and radiation risks. Consequently, each technology demands dedicated risk management and safety protocols tailored to its specific hazards, ensuring that the benefits of AM can be realised without compromising worker health and safety.

In the automotive sector, technologies such as Powder Bed Fusion, Material Extrusion, and Directed Energy Deposition are among the most commonly used. These technologies are integral in manufacturing structural components, prototypes, tooling aids, and repair parts, making them central to both innovation and production efficiency.

RISK ASSESSMENT IN AUTOMOTIVE INDUSTRY AM

Effective risk assessment in automotive AM environments is essential not only for safeguarding the health and safety of workers but also for maintaining compliance with increasingly stringent regulatory standards.

As AM technologies become more deeply integrated into automotive industry workflows, the complexity and variety of associated occupational hazards increase. Workers involved in AM processes are frequently exposed to fine and ultrafine metal and polymer particles, volatile organic compounds, toxic fumes, and high-energy sources such as lasers, electron beams, or ultraviolet radiation. These exposures can result in a range of acute and chronic health effects, including respiratory illnesses (e.g., asthma, chronic bronchitis), dermal reactions, chemical burns, and even long-term risks such as carcinogenicity and systemic toxicity from nanoparticle accumulation.

Risk assessment plays a pivotal role in identifying, quantifying, and prioritising these hazards based on their likelihood, severity, and frequency of occurrence. A structured assessment process enables organisations to develop a clear understanding of workplace risks and implement targeted, effective mitigation strategies.

Beyond protecting individual health, comprehensive risk assessment supports environmental sustainability by promoting responsible material selection and process optimisation. By identifying harmful substances early in the design or planning phase, automotive manufacturers can substitute hazardous inputs with safer alternatives or adopt additive processes that generate less waste. Proper containment and disposal of residual powders, resins, and byproducts also contribute to reduced environmental impact and alignment with environmental legislation such as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) and OSHA (Occupational Safety and Health Administration) regulations.

Key definitions - understanding safety terminology in automotive industry AM environments

A comprehensive and legally compliant risk assessment begins with a clear understanding of the key terms that define workplace safety and hazard management. According to the *Serbian Occupational Safety and Health Law* (as published in the 'Official Gazette of the Republic of Serbia,' No. 35/2023), several foundational concepts underpin the assessment of occupational risks, especially in complex and evolving industrial environments such as those involving AM in the automotive industry.

First and foremost, a hazard is defined as any circumstance, situation, or condition that has the potential to cause injury, illness, or damage to human health. In the context of AM technologies, this could include the presence of moving mechanical parts, exposure to high temperatures, the use of lasers or ultraviolet light, and the handling of reactive chemical substances such as photopolymers or fine metal powders. Hazards are often embedded in routine production activities and may not always be immediately apparent, making their identification a critical first step in the risk management process.

Closely related to hazards is the concept of harmfulness, which refers to the inherent properties of a substance, process, or condition that can negatively affect human health. While a hazard represents a potential danger in the workplace, harmfulness focuses on the capacity of a specific material or exposure to actually cause harm. For instance, in AM processes used in automotive applications, the harmfulness of airborne nanoparticles generated during powder bed fusion or directed energy deposition lies in their ability to penetrate deep into the lungs, enter the bloodstream, and possibly lead to long-term systemic health effects. Basically, harmfulness is defined as a hazard whose consequences manifest over an extended period of time.

Risk is the product of the probability that a hazardous event will occur and the severity of its possible consequences. It quantifies the likelihood and potential impact of harm arising from exposure to a particular hazard. In practical terms, risk in an AM-enabled automotive industry environment might involve assessing how often workers are exposed to fine particulate emissions from a 3D printer, and the seriousness of the health outcomes if those particles are inhaled regularly. This probabilistic approach to risk allows for prioritisation - enabling safety managers to focus first on high-risk scenarios that pose the most serious threat to workers.

The cornerstone of occupational safety practice is the risk assessment, defined in the Serbian legal framework as a systematic process for identifying hazards, evaluating associated risks, and determining suitable control measures to eliminate or mitigate them. This process involves a thorough examination of the workplace, machinery, materials, and workflows, followed by an analysis of the likelihood and severity of potential incidents. In the automotive industry, where AM is increasingly utilised to produce structural components, tooling, and customised parts, risk assessment must be tailored to the specific technologies in use - considering factors such as the types of raw materials, the energy sources employed, and degree of worker interaction with machines.

Risk assessment methods in the context of automotive industry AM

In the automotive industry, where AM is becoming an essential component of production and design, selecting the appropriate risk assessment methodology is critical to ensuring worker safety, operational continuity, and regulatory compliance. A range of well-established methods is commonly employed across industries to conduct risk assessments, each with its own strengths and limitations, /7/.

One widely used approach is Failure Mode and Effects Analysis (FMEA), a systematic technique that identifies potential failure modes within a system, assesses their effects on overall operations, and prioritises them based on severity, occurrence, and detectability. It is especially useful in complex mechanical or electronic systems where anticipating and mitigating failures can prevent costly downtime or hazardous situations. In the context of AM, FMEA can help evaluate design flaws, equipment malfunctions, or material inconsistencies that might pose safety risks or compromise product quality.

An extension of this method is Failure Mode, Effects, and Criticality Analysis (FMECA), which adds a criticality ranking to each failure mode, providing a more granular understanding of which failures are most urgent to address. FMECA is particularly valuable in high-stakes automotive applications where AM components are used in safety-critical systems, such as braking assemblies or structural supports.

Fault Tree Analysis (FTA) offers a top-down, deductive approach, beginning with a defined undesirable event - such as an equipment fire or chemical spill - and mapping out all possible causes through a tree-like diagramme of logical relationships. This visual and analytical technique is highly effective in identifying multiple failure paths, especially in systems where human-machine interaction plays a significant role, as is often the case in AM-based production lines.

The Singapore Model, also known as the 3x3 matrix, provides a simplified risk assessment framework by evaluating the severity and likelihood of hazards across a basic grid. It is often used for quick assessments and decision-making in lower-risk environments or for screening purposes before applying more complex methods.

While these traditional risk assessment tools are robust and widely applicable, they face practical limitations when applied directly to AM processes - especially in the automotive industry. AM is characterised by a wide array of input materials, including polymers, metals, ceramics, and composite resins, each with distinct chemical and physical hazards. Moreover, AM systems involve tightly integrated hardware and software components, requiring operators to interact with sophisticated machinery, high-energy sources (e.g., lasers, electron beams), and digital workflows. This technological complexity and material diversity challenge the applicability of methods that are primarily designed for linear, well-defined systems.

Given these challenges, this research adopts the Kinney risk assessment method /8/ which offers greater adaptability for the diverse and evolving landscape of AM. The Kinney method evaluates risk through a simple but effective formula that incorporates three key factors: the probability of occurrence, the severity of potential harm, and the frequency of exposure. The resulting risk score enables clear categorisation into risk levels, supporting practical decision-making and prioritisation of control measures.

What makes the Kinney method particularly suitable for AM in automotive settings is its flexibility in handling both qualitative and semi-quantitative data. It allows assessors to incorporate expert judgment, real-world exposure data, and process-specific considerations, which are often difficult to quantify precisely in high-variability environments like AM production.

The Kinney risk assessment method

The Kinney risk assessment method provides a structured approach to evaluating workplace hazards by assigning numerical values to three key factors: the probability of an incident occurring, the severity of potential consequences, and the frequency of worker exposure to the hazard /8/. This semi-quantitative model offers a practical way to prioritise risks and determine the appropriate level of intervention.

The method calculates overall risk using Eq.(1):

$$\text{Risk(R)} = \text{Probability(V)} \times \text{Severity(P)} \times \text{Frequency(U)} \qquad (1)$$

Each component of the formula, described in Table 1, is rated on a scale that reflects its impact on overall safety:

Probability (V): this represents the likelihood that a hazardous event will occur. A score of 0,1 indicates that the event is almost inconceivable, while a score of 10 suggests that the hazard is highly likely or imminent.

Severity (P): this assesses the magnitude of harm the hazard could cause. A score of 1 indicates a minor injury, such as a scratch or mild irritation, whereas a score of 10 corresponds to life-threatening injuries or fatalities.

Frequency (U): this shows how often workers are exposed to the hazard. A score of 1 is used when exposure is rare or infrequent, and a score of 10 is used when the exposure is constant or occurs during every shift.

Table 1. Description of criteria for assessing probability, severity, and frequency, /8/.

V	Description of criteria for assessing probability	P	Description of criteria for assessing severity	U	Description of criteria for assessing frequency
0.1	Barely conceivable	1	Illness or injury requiring only first aid and no further treatment	1	Exposed rarely (annually)
0.2	Practically impossible	2	Medical treatment provided by a physician	2	Exposed monthly
0.5	Exists, but only slightly probable	3	Serious - disability or major individual injury requiring hospitalization and lost workdays	3	Exposed weekly
1	Low probability, but possible in limited cases	6	Very serious - individual accidents resulting in fatality	6	Exposed daily
3	Unlikely	10	Catastrophic - multiple fatalities	10	Exposed continuously, permanently
6 10	Quite possible predictable, expected				

Once these values, are assigned and multiplied, the resulting risk score falls into one of five levels, which guide the appropriate response:

- RI (0.1-20): Negligible risk. No immediate action is necessary, but the situation should be periodically reviewed.
- RII (21-70): Low risk. Monitoring is advised, and improvements may be implemented as a precaution.
- RIII (71-200): Medium risk. Corrective measures should be taken to reduce risk to an acceptable level.
- RIV (201-400): High risk. Work involving this hazard should stop until sufficient control measures are in place.
- RV (> 400): Extreme risk. This level indicates a critical danger. The activity must be completely prohibited until the risk is mitigated or eliminated.

This categorisation, shown in Table 2, enables decision-makers in automotive industry to clearly see which aspects of their AM processes demand urgent attention - whether it is exposure to toxic resin vapours during stereolithography or the risk of thermal burns from high-energy fusion processes.

Table 2. Criteria for determining risk levels, /7/.

Risk level (R)	0.1-20	21-70	71-200	201-400	Over 400
Risk level classification	Negligible risk	Low risk	Medium risk	High risk	Extreme risk

Using checklists to identify hazards and harmful effects

To apply the Kinney method effectively, a systematic identification of potential hazards is required. For this purpose, checklists based on the ISO 12100:2010 standard (Safety of Machinery - General Principles for Design - Risk Assessment and Risk Reduction) /9/ are employed, Tables 3 and 4. These checklists guide safety engineers and managers through various types of risks commonly found in industrial settings.

The hazard checklist includes categories such as:

- *Mechanical hazards*, like moving or rotating parts that can cause entanglement or crushing injuries;
- *Electrical hazards*, such as exposure to live circuits or thermal effects caused by overheating;
- *Fire and explosion hazards*, especially when working with flammable powders or reactive chemical materials.

The harmfulness checklist addresses the potential adverse effects of exposure, including:

- *Chemical harmfulness*, such as inhalation or skin contact with resins, solvents, and nanoparticles;
- *Radiation harmfulness*, which may stem from lasers, UV light, or electron beams used in certain AM technologies;
- *Organisational factors*, including long shifts, emergency response preparedness, or inadequate rest periods, which can exacerbate physical or psychological strain.

Table 3. Hazard checklist.

Hazard group	Code	Hazard subgroup	YES/NO checklist
Mechanical hazard associated with the use of work equipment	(1)	Insufficient safety due to rotating or moving parts	
	(2)	Free movement of parts or materials that may cause injury to employees	
	(3)	Internal transport and movement of work machines or vehicles, as well as relocation of certain work equipment	
	(4)	Use of hazardous work substances that may cause explosions or fire	
	(5)	Inability or limitation to promptly leave the workplace, exposure to entrapment, mechanical impact, crushing, etc.	
	(6)	Other factors that may appear as mechanical sources of hazards	
Hazard related to workplace characteristics	(7)	Dangerous surfaces	
	(8)	Work at height or depth, according to occupational safety and health regulations	
	(9)	Work in confined, restricted, or hazardous spaces	
	(10)	Risk of slipping or tripping	
	(11)	Physical instability of the workplace	
	(12)	Possible consequences or disturbances due to mandatory use of personal protective equipment	
Hazard related to workplace characteristics	(13)	Effects from performing work processes using inappropriate or unsuitable working methods	
	(14)	Other hazards that may arise in connection with workplace characteristics and work methods	
Hazard associated with the use of electrical energy	(15)	Hazard of direct contact with parts of electrical installations and equipment under voltage	
	(16)	Hazard of indirect contact	
	(17)	Hazard from thermal effects generated by electrical equipment and installations	
	(18)	Hazards due to lightning strikes and atmospheric discharges	
	(19)	Hazard from harmful effects of electrostatic charging	
	(20)	Other hazards that may arise in connection with the use of electrical energy	

Table 4. Harmfulness checklist.

Harmfulness group	Code	Harmfulness subgroup	YES/NO checklist
Harmfulness that arises or occurs during the work process	(21)	Chemical harmfulness, dust, and fumes	
	(22)	Physical harmfulness	
	(23)	Biological harmfulness	
	(24)	Harmful effects of microclimate	
	(25)	Inappropriate or insufficient lighting	
	(26)	Harmful effects of radiation	
	(27)	Harmful climatic effects	
	(28)	Harmfulness arising from the use of hazardous substances in production, transport, packaging, storage, or disposal	
	(29)	Other harmfulnesses appearing during the work process that may cause occupational injury, occupational disease, or work-related illness	
Harmfulness originating from mental and psychophysiological strains causally linked to the workplace and tasks performed by employees	(30)	Physical exertion or strain	
	(31)	Non-physiological body posture	
	(32)	Efforts in performing certain tasks causing psychological stress	
Harmfulness originating from mental and psychophysiological strains causally linked to the workplace and tasks performed by employees	(33)	Responsibility in receiving and transmitting information, using appropriate knowledge and skills, responsibility for behavioural rules, responsibility for rapid changes in work procedures, work intensity, spatial conditions of the workplace, conflict situations, working with clients and money, insufficient motivation for work, responsibility in management, and similar	
Harmfulness related to work organization	(34)	Work longer than full working hours, shift work, reduced working hours, night work, on-call readiness for interventions	
Other harmful activities that appear at workplaces	(35)	Harmfulness caused by other persons	
	(36)	Work with animals	
	(37)	Work in high or low-pressure atmospheres	
	(38)	Work near or under water	
	(39)	Other hazards and harmfulness	

RISK ASSESSMENT RESULTS FOR AUTOMOTIVE INDUSTRY AM TECHNOLOGIES

Drawing on the comprehensive completion of hazard and harmfulness checklists alongside the systematic application of the Kinney risk assessment method, Table 5 delineates the calculated average risk values for various AM technologies as classified by the ASTM ISO/ASTM 52900-21 standard /6/. These quantitative risk assessments provide a crucial comparative overview of the occupational hazards inherent to each AM process, reflecting both mechanical and chemical risks tailored to the unique characteristics of each technology.

Table 5. Estimated average risks of different types of AM technologies, /10/.

Type of AM technology	Average risk value from identified hazards	Average risk value from identified harmfulness
Vat photopolymerization	31.00	220.00
Material jetting	34.60	220.00
Binder jetting	28.20	233.33
Powder bed fusion	29.50	176.50
Material extrusion	84.75	166.67
Directed energy deposition	42.83	250.00
Sheet lamination	47.25	233.33

To ensure the robustness and reliability of these findings, the risk values have been cross-referenced and harmonised with data from existing scholarly and industrial literature, as outlined in /7/. This alignment not only validates the current assessment but also situates it within the broader context of ongoing research into AM safety. The table uses a clear visual coding system: the highest average risk scores are prominently highlighted in red to signal areas of critical concern requiring immediate attention, while the lowest risk values are marked in green, indicating relatively safer operational conditions.

The method for deriving these average risk values involves calculating the arithmetic mean of individual partial risk scores. These partial scores correspond to specific hazards and harmfulness factors identified for each AM technology - such as mechanical dangers, chemical exposures, radiation, or thermal risks - which are systematically evaluated through the checklists. This approach allows for a nuanced understanding of the overall risk profile associated with each AM process rather than relying on a singular hazard perspective.

Based on the data presented in Table 5, the types of AM technologies that exhibit the highest average risk values - both in terms of identified hazards and harmfulness - have been clearly determined. Among the technologies analysed, the *Material extrusion* process, commonly represented by *Fused filament fabrication* (FFF), stands out as having the highest average risk related to hazards such as mechanical injuries and thermal exposure.

To provide a deeper understanding of these risks, Table 6 offers a detailed overview of estimated risk values associated specifically with the *Material extrusion* process. This process involves heating thermoplastic materials and extruding them through a nozzle to build objects layer by layer. Although Material extrusion is one of the most widely used and accessible AM technologies, particularly for rapid prototyping and the production of jigs and fixtures in the automotive industry, it carries significant occupational safety risks if not properly managed.

Key hazards in Material extrusion arise from contact with moving mechanical components, such as the extruder head and build platform, as well as exposure to high temperatures that can cause burns. The risk of electrical hazards is also present, especially in environments lacking regular maintenance or electrical safety inspections. Additionally, the inhalation of heated plastic fumes - which may contain volatile organic compounds (VOCs) - can pose health risks to workers over time.

Table 6. Estimated risk values for hazards and harmfulness associated with the use of *Material extrusion* technology, /7/.

Hazards/ harmfulness	Description	Consequences	V	P	U	Risk
Insufficient safety due to rotating or moving parts	Extruder moving head	Possible burns and physical injuries	10	1	10	100
Hazardous surfaces (floors and all types of treads, surfaces with which the employee comes into contact, which have sharp edges - edges, spikes, rough surfaces, painted parts	Obtaining sharp parts, removing support	Possible cuts	6	1	6	36
Hazard from direct contact with live parts of electrical installations and equipment	The device is powered by electricity.	Electric shock, burns, injury due to the explosion	0.5	6	1	3
Hazard from thermal effects developed by electrical equipment and installations (overheating, fire, explosion, electric arc or sparking, etc.)	Heated extruder head and worktable	Possible burns	10	2	10	200
Chemical harmfulness, dust and fumes (inhalation, suffocation, ingestion, penetration into the body through the skin, burns, poisoning, etc.)	Emission of harmful gases when obtaining a part	Possible nausea, headache, poisoning	10	3	10	300
Working longer than full-time (overtime), shift work, part-time work, night work, emergency standby intervention	Working beyond working hours, night shifts, possible emergency interventions	Physical fatigue	10	1	10	100

Table 7 provides a comprehensive analysis of estimated risk values associated with *Directed energy deposition*, an advanced AM technology that has been identified as posing the highest average risk in terms of harmfulness to workers' health and safety, according to the data presented in Table 5. This technology, used in the automotive industry for the repair, enhancement, and fabrication of metal components, involves the use of focused thermal energy sources - such as lasers, electron beams, or plasma arcs - to fuse metal powder or wire onto a substrate.

While *Directed energy deposition* offers unique benefits in terms of material efficiency, part complexity, and the ability to restore high-value automotive components, it also introduces significant occupational health challenges. The primary risks stem from the generation of fine metallic particles, toxic fumes, and the exposure to intense thermal and electromagnetic radiation. Inadequate ventilation or lack of proper protective equipment can lead to serious long-term health issues, including respiratory diseases, skin damage, or even carcinogenic effects due to chronic exposure to hazardous substances.

Table 7. Estimated risk values for hazards and harmfulness associated with the use of *Directed energy deposition*, /7/.

Hazards/ harmfulness	Description	Consequences	V	P	U	Risk
Insufficient safety due to rotating or moving parts	Moving head	Physical injuries, burns	3	2	10	60
Using hazardous materials that can cause explosions or fires	Using powders	Possible fire, explosion, causing burns	0.5	10	10	50
Hazardous surfaces (surfaces that the employee comes into contact with, which have sharp edges - edges, spikes, rough surfaces, etc.)	Getting sharp parts, removing support	Possible cuts	6	2	6	72
Hazard from direct contact with live parts of electrical installations and equipment	The device is powered by electricity	Electric shock, burns, injury due to the explosion	0.5	10	1	5
Hazard from thermal effects generated by electrical equipment and installations (overheating, electric arcing or sparking, etc.)	Heated material and the resulting part	Possible burns	10	1	6	60
Chemical harmfulness, dust and fumes (inhalation, suffocation, ingestion, penetration into the body through the skin, burns, etc.)	Using powders	Possible inhalation of toxic fumes, inhalation of dusts	10	3	10	300
Harmful effects of radiation (ionizing or non-ionizing, laser, ultrasound)	Electron beam, laser radiation	Eye and skin damage	10	3	10	300
Harmfulness resulting from the use of hazardous substances in production, transport, packaging, storage or destruction	Use of powders and wires in the production of parts	Possible inhalation of toxic fumes, inhalation of dusts	10	3	10	300

DISCUSSION OF RISK ASSESSMENT RESULTS AND PROPOSAL OF SAFETY MEASURES

Based on the presented results, it can be concluded that among the various risks associated with AM technologies, chemical hazards represent the most significant threat to worker health and safety. A wide range of materials used in AM processes - including polymers, resins, and metal powders - emit harmful particles, volatile organic compounds, fumes, and gases during processing. These substances pose both acute and chronic health risks, including respiratory irritation, chemical burns, and in some cases, long-term toxic or carcinogenic effects.

To mitigate these risks, it is essential to implement comprehensive protective strategies. Workers must use appropriate personal protective equipment, such as respirators or filtered masks, chemical-resistant gloves, safety goggles, lab coats, and antistatic suits. Equally important is the requirement for well-ventilated working environments, preferably equipped with localised exhaust ventilation or High-Efficiency Particulate Air (HEPA) filtration systems. For smaller AM units, placing machines in enclosed housings or fume extraction chambers can further reduce exposure. Moreover, where feasible, manufacturers should prioritise the use of materials with lower emission profiles and minimal chemical reactivity.

In addition to the chemical risks, many AM materials present a fire and explosion hazard, especially when working with fine metal powders or flammable resins. To reduce this risk, it is critical to follow manufacturer guidelines for storage, handling, and disposal of hazardous materials. Proper grounding, humidity control, and antistatic equipment can also prevent the buildup of electrostatic charges that may ignite airborne particles.

Another significant category of hazards in AM processes involves radiation exposure, particularly in technologies such as *Directed energy deposition* or *Powder bed fusion*, which utilise lasers or electron beams. To protect workers from optical, ionizing, or thermal radiation, the use of radiation-shielding machine enclosures and laser safety eyewear is mandatory. Contact with the machine should be strictly avoided while the radiation source is active, and interlock systems should be in place to ensure compliance.

Furthermore, AM operations expose workers to mechanical and thermal hazards. Moving parts, such as print heads or rotating build platforms, and high-temperature components create the potential for cuts, crush injuries, and burns. These risks can be mitigated by using appropriate PPE, clearly marked hazard zones, and enforcing procedures that prohibit direct contact with operating machinery. It is also advisable to allow a cooling period of at least 30 minutes before handling printed parts, particularly those produced through extrusion or laser-based processes.

An often-overlooked risk factor in AM environments is the organisational strain placed on workers. Many AM operations require extended work hours, night shifts, and immediate emergency responses, which can lead to worker fatigue, stress, and reduced concentration, all of which elevate the risk of accidents. A reduction in this risk can be achieved through workload sharing, task rotation, and ensuring adequate rest and recovery time for personnel.

To address these multidimensional risks, it is essential that organisations develop clearly defined operational procedures, enforce safety protocols, and invest in ongoing worker training. Regular education sessions focusing on new developments in AM technologies, emerging risk factors, and appropriate responses can significantly enhance workplace safety. Additionally, continuous health monitoring and routine risk re-evaluations are recommended, particularly in facilities where high-risk technologies such as *Directed energy deposition* or *Powder bed fusion* are in use.

CONCLUSION

Additive manufacturing (AM) technologies have become an integral component of the modern automotive industry, fundamentally transforming the way vehicles are designed, prototyped, and produced. By facilitating the fabrication of lightweight, geometrically intricate, and highly customised components, AM drives innovation across the sector, enabling manufacturers to improve performance, reduce emissions, and maintain a competitive edge in an increasingly dynamic global market. However, alongside these technological benefits, the integration of AM into industrial workflows introduces a complex array of occupational hazards and harmful exposures - many of which are still insufficiently explored in scientific literature and inadequately addressed by current regulatory frameworks.

This research employed the Kinney risk assessment method to systematically evaluate and quantify occupational risks associated with different AM technologies used in automotive manufacture. The analysis identifies *Material extrusion* (*Fused filament fabrication*) as the technology posing the highest mechanical and thermal risk to operators, primarily due to its moving components, high operating temperatures, and the emission of heated plastic fumes. In contrast, *Directed energy deposition* is determined to present the most serious harmfulness risks, including chronic exposure to toxic metal fumes, fine particulate matter, and high-intensity thermal and electromagnetic radiation. These findings underscore the critical need for technology-specific safety protocols and proactive risk mitigation strategies.

In light of these results, this research advocates for the immediate implementation of targeted protective measures. These include the use of advanced ventilation systems equipped with HEPA filtration, mandatory deployment of personal protective equipment, integration of real-time hazard detection systems, and the adoption of engineering controls such as fully enclosed printing environments and automated material handling systems. Beyond technical interventions, the human factor must also be addressed through structured training programmes, safety drills, and continual education on emerging risks associated with AM technologies.

Moreover, the research highlights the importance of harmonising industrial AM practices with internationally recognised safety standards, such as ISO 12100 (general principles for risk assessment and reduction) and ASTM ISO/ASTM 52900-21 (classification and terminology of AM processes). It also stresses the necessity of adapting and updating national occupational safety regulations - such as those established under Serbian law - to better reflect the specific hazards inherent in AM operations.

Ensuring the safe, sustainable, and responsible adoption of additive manufacturing requires an ongoing commitment to comprehensive risk assessment, cross-disciplinary collaboration between engineers, safety professionals, and health experts, and the proactive development of flexible safety standards capable of evolving alongside technological advances. Future research should place greater emphasis on the long-term health effects of nanoparticle exposure, cumulative impacts of chronic chemical and radiation exposure, and the design of data-driven safety frameworks supported by digital monitoring and predictive analytics. By embedding a culture of risk management within the innovation cycle, the automotive industry can fully leverage the transformative potential of AM - while upholding its duty to protect worker health, ensure regulatory compliance, and contribute to broader sustainability and safety objectives.

ACKNOWLEDGEMENT

The authors sincerely appreciate the support of the relevant ministries of the Republic of Serbia and the Slovak Republic in facilitating this research. The research is conducted as part of the bilateral project No. 337-00-3/2024-5/08, within the 2024-2025 bilateral cooperation cycle between Serbia and Slovakia.

REFERENCES

1. Pejčić, D., Mišković, Ž., Antić, J., et al. (2025), *Vat photopolymerization risk assessment using the Kinney method*, In: Proc. 11th Int. Conf. Research and Development of Mechanical Elements and Systems (IRMES 2025), Vrnjačka Banja, Serbia, pp.113-118. doi: 10.46793/IRMES25.113P
2. Trajković, I., Balać, M., Milošević, M., Međo, B. (2025), *Application of the dic method in determining fracture mechanics parameters on ring-shaped specimens with a sharp notch manufactured using the FDM technique*, Struct. Integr. Life, 25(1): 127-133. doi: 10.69644/ivk-2025-01-0127
3. Milovanović, A., Sedmak, A., Paunić, M., et al. (2024), *Tensile properties of pure PLA polymer dedicated for additive manufacturing*, Struct. Integr. Life, 24(3): 263-268. doi: 10.69644/ivk-2024-03-0263
4. Jevtić, I., Stojanović, J., Milovanović, A., et al. (2024), *Printing orientation and place influencing the compressive strength of polyamid 12 specimens obtained by SLS technology*, Struct. Integr. Life 24 (1): 3-7. doi: 10.69644/ivk-2024-01-0003
5. Alijagić, A., Engwall, M., Särndahl, E., et al. (2022), *Particle safety assessment in additive manufacturing: From exposure risks to advanced toxicology testing*, Front Toxicol. 4: 1-22. doi: 10.3389/ftox.2022.836447
6. ASTM ISO/ASTM52900-21: Additive manufacturing - General principles - Fundamentals and Vocabulary, pp.1-6, 2021.
7. Pejčić, D., *Risk assessment of additive manufacturing technologies*, M.Sc. Thesis, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia, 2024.
8. Stanković, M., Stanković, V. (2013), *Comparative analysis of methods for risk assessment – "KINNEY" and "AUVA"*, Safety Eng. 3(3): 129-136. doi: 10.7562/SE2013.3.03.04
9. ISO 12100:2010: Safety of machinery - General principles for design - Risk assessment and risk reduction, pp. 1-77, 2010.
10. Pejčić, D., Mišković, Ž., Popović, M., et al. (2024), *Risk assessment of additive manufacturing technologies using the Kinney method*, In: Proc. 44th Conf. JUPITER 2024, Belgrade, Serbia, ISBN 978-86-6060-204-8, pp. 2.52-2.57.