



Volume 111

2021

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: <https://doi.org/10.20858/sjsutst.2021.111.4>



Journal homepage: <http://sjsutst.polsl.pl>

Article citation information:

Galik, J., Kohar, R., Brumercik, F., Hudec, J., Patin, B. Increasing the safety of a device using the TRIZ methodology. *Scientific Journal of Silesian University of Technology. Series Transport*. 2021, **111**, 43-56. ISSN: 0209-3324.

DOI: <https://doi.org/10.20858/sjsutst.2021.111.4>.

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INCREASING THE SAFETY OF A DEVICE USING THE TRIZ METHODOLOGY

Summary. The safety of machinery is a very important aspect for its correct functioning in the conditions of modern production or assembly. According to the standards, manufacturers of special-purpose machines and devices are obliged to provide their equipment with a certificate of conformity (CE). This article describes the concerns of insufficient safety of a device. Insufficient coverage of part of the line meant that the certification did not take place, and the safety requirements were not met. The TRIZ method was used to resolve this technical discrepancy, providing designers with "instructions" on how to proceed, solve complex problems at the level of discrepancies and create solutions. By agreement of the designers, a solution that was not economically and implementation-intensive was created. All doors and windows within the fencing have been reinforced, thus achieving

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a greater degree of security. The resulting solution was subjected to simulations in the Ansys Workbench program, and the FEM analysis led to certain conclusions. The results were then moved to the structural engineer to assess the solution, who then approved the solution and successful certification of part of the device, respectively, in the assembly line.

Keywords: special-purpose machines, safety, TRIZ

1. INTRODUCTION

Companies operating in the engineering industry are very complex units, containing various types of production and assembly technologies. With the increasing degree of automation, the complexity of decision-making processes within production or assembly increases. An important factor is the degree of automation of machinery and equipment, whether manual, semi-automated or automated equipment [1-3]. A large range of robotic devices can be observed in production. There are different classes and types of robots suitable for different activities. Inter-operational robots usually have the task of moving parts, rotating them, storing them, etc. Production robots have the task of either assisting man with manipulation or functioning independently in the production process in place of the man [4]. A great help in assembly logistics is, for example, AGV tractors [5].

The devices consist of various programmable modules and control units [6]. These modules ensure security and are included in the price offers as an option to purchase the device [7]. The company was approached by a new customer with a problem related to the line, specifically the robotic workplace. The essence was to increase the safety of a device, and the problem was that the inspection of the device in obtaining a CE certificate was not successful [8]. The TRIZ methodology is often used within the company, which provides its view of the solved problem [9-11]. The company proposed a solution right at the certification regarding the inclusion of light gates, which would work as interrupters of the device. They would react to possible damage to the fence; thus, increase the level of security [12, 13]. Although the Slovak Technical Inspectorate is the certifier, it was not enough as a solution that would increase the strength of the fencing was needed [14]. After determining the solution and limiting conditions, the results had to be substantiated by FEM analysis. Ansys Workbench was available from the available software [15, 16]. The specific case was solved in cooperation with the company HJ Design s.r.o.

1.1. Workplace safety

Devices safety is a relevant element in the proper functioning of equipment as a whole. The Safety Act defines that the employer is obliged to ensure that the work device he/she provides to the employee complies with the minimum safety requirements required of it. The safety of the work device can also be understood as a safe installation and inspection at the required location. Installation and proper use mean the assembly of a functional unit, located in the employer's premises, its proper functioning and connection, for example, for electrical installation, pressure distribution (compressed air, nitrogen, etc.), hydraulic distribution, air conditioning, and distribution of waste materials [17-19]. The safety of the devices is verified by the customer's requirements, within the standards, while the electrical safety of the device must be subject to both the STN 331600 and STN 331610 standards [20]. A large number of requirements for new equipment is considered by designers during the design process [21].

An important aspect is the degree of automation of the device (assembly line, etc.). From this viewpoint, we know from the human operation, semi-automatic and automatic workplaces. As part of security, different automated devices are also treated differently. Standards EN ISO 10218-1 and EN ISO 10218-2 deal mainly with the environment of industrial robots [22]. These standards point out the possible risks associated with robots and the conditions for eliminating these risks. It is necessary to follow the established rules such as no entry of unauthorised persons into the range of the robotic arm, robot speed below 250 mm/s, entry into space only without automatic mode, the control panel must be held in the hand and the robot is not controlled externally and so on [23].

Based on the analysis of possible risks and the determination of restrictive conditions, several safety elements are used in the production cell, namely: fencing, protection of access doors, and emergency stop [24]. Fencing has the function of protecting the surroundings against possible robot-surroundings collisions. In the event of an impact, fencing should absorb a larger part of the energy; thus, protect the environment against the action in our case of the robotic arm. As part of the requirements, or in an agreement between the customer and the manufacturer, a way of fencing with the BOSCH REXROTH AG modular system was specified, which uses modular types of aluminium profiles and a whole range of various additional modules and design improvements [25, 26]. The construction created by the designer seemed to be sufficiently strong, which according to them, needs no additional modification. To protect the operator, it is possible to use either fencing or frequently used polycarbonate boards.

The construction uses a security lock as one of the other security elements. With a higher degree of automation, the door parts of the fence must be protected thus [27]. They tend to combine modules such as a handle (mechanical system) and sensors (electrical system) to create a mechatronic system. There are different variants of security locks, most of which are designed as modular systems, where a specific lock can be extended by an additional module [28]. Currently, there are many companies (Euchner, Sick, Troax, and others) that think this way because modular systems save energy, costs, and time [29]. The protection elements can also include the use of a T switch, which serves as a safety mechanism. Upon pressing it, the operation of the device is immediately interrupted, often of the entire line.



Fig. 1. Fencing of a robotic workplace



Fig. 2. Fencing of a robotic workplace

The problem arose on the part of the assembly line where the robotic arm is installed behind the safety fencing (in the cage). According to the standards, and the technical inspection, the given device is unsatisfactory from a safety perspective; it is necessary to correct the current state, and only then can the device obtain a CE certificate. The technical inspection does not give an official permit for the operation of such equipment. Certificates according to Act 124/2006 Coll. discuss the safety of technical equipment [20]. In Figures 1 and 2, it is possible to see three walls of the fences in the robotic workplace in which a collision can occur. The result can be a fatal collision with the person standing next to it.

Due to various factors, a specific workplace creates danger for human operators, which is an unacceptable situation from the position of safety and health at work. The standard STN EN ISO 14121-1: 2008 deals with the assessment of risks in all phases of the life of machinery. The functional safety of the machine is discussed in STN EN ISO 13849-1: 2008 [30]. According to these standards, equipment put into operation is not completely in order. The biggest problem is that due to the spatial possibilities and the robotic arm used, there is still the possibility of a collision with the protective fencing.

The robotic arm used is from Mitsubishi, type RV-7FM-D1-S15, while cooperating with the robotic controller type CR750-07VD1-1-S15. As part of the purchase of the device from a subcontractor, it was possible to purchase a module to protect the device from damage (possible collision) [31]. The function of this module is to protect the device and prevent the robotic arm from moving out of its confinement. Due to an insufficient budget, the purchase of this option was rejected. Based on the customer's request, the concept of increasing the safety of the robotic device was proposed. The TRIZ methodology proved to be very reliable, not only in the phase of the ideological (conceptual) solution but also in solving various technical problems and contradictions.

2. TRIZ METHODOLOGY AND PROBLEM SOLVING

Based on previous experience, the TRIZ method has proved its worth in solving various problems, providing good solutions to problems where technical or physical contradictions arise in proposed solutions. The term contradiction can be understood that by increasing the value of one parameter, we achieve a decrease in the value of another parameter, which is important to us. This method is innovative and provides the key to overcoming contradictions through various solutions [7, 32, 33].

The main problem solved was insufficient safety of the working robot. Safety had to be increased, so the question was "How?". When considering this problem, another condition was encountered, and it sounded at least interfering with the existing construction of the workplace [34, 35].

Using the TRIZ methodology, a key technical discrepancy was determined, which arose from the relationship between the stability of the building (fencing) - 13 and the adaptability of the building (fencing) - 35 (Figure 3). By increasing the stability of the fence, we can strengthen the fence, however, this makes it unable to adapt to a possible impact. By increasing the adaptability, we can achieve low stability of the building, that is, the fencing may withstand the impact; however, there will be a deviation from the cage, which is unacceptable for technical inspection (light gates - Section 1). According to Altshuller's table, the problem (contradiction) can be solved by several possible approaches, namely flexible coatings or membranes (35), recycling and regeneration (34), separation of the part (2), or change of physical or chemical properties (30).

The solution principle with flexible coatings or membranes can be used to increase the safety of the device (35). An example would be the use of impacting a panel of doors and walls covered with a durable coating. Based on available resources, this principle cannot be used to solve this situation, thus, a simple and effective solution is needed.

		Weight of the moving object	Weight of stationary	...	Adaptability or versatility	...	Productivity
		1	2	...	35	...	39
1	Weight of moving object	-	-	...	29, 5, 15, 8	...	35, 3, 24, 37
2	Weight of stationary	-	-	...	19, 15, 29	...	1, 28, 15, 35
...
13	Stability of the object	21, 35, 2, 39	26, 39, 1, 40	...	35, 30, 34, 2	...	23, 35, 40, 3
...
39	Productivity	35, 26, 24, 37	28, 27, 15, 3	...	1, 35, 28, 37	...	-

Fig. 3. Technical discrepancy of construction in the Altshuller matrix

Another solution provided was the use of recovery and recycling (34). This solution option is used, for example, when one part of the whole (no longer needed part) evaporates, resp. disappears during operation, or a regeneration and recovery process may occur. In our case, the team of designers did not figure out how to solve the problem in this way.

The third principle of solving our problem is to separate the influencing part from the whole, to separate it (2). An example is a compressor room, which due to noise from compressors and vibrations, is separated from the consumer of compressed air while the person only has a compressed air connection located next to him/her. There were no ideas or feedback from the team to use this principle.

The last usable principle from the Altshuller table was the principle of changing the physical state (30), for example, a change to a gas or liquid, or a change in other physical properties. Upon closer examination and consultation of the design team regarding this principle, it was concluded that there is a possibility to increase the flexibility of the fence, and at the same time, reinforce the fence with the least possible intervention and the lowest possible production costs - assembly. Based on another consultation, several variants of resolving the situation were created.

2.1. Solution variants

Based on the information available so far, several ideas have emerged on how to strengthen the structure and create a stronger fence of the robotic arm, which would withstand a possible collision. Thus, it has to be a simple, economically undemanding solution that can be quickly implemented. Given the solution to the discrepancy from the previous section, the design team tried to provide the necessary solutions to the situation.

The first proposal was to simply reinforce a given existing structure so that the existing window of the structure and the door could be easily divided by a profile. This would create reinforcement and require smaller plexiglass, which can effectively increase the strength of the construction of all three walls-doors. From an economic standpoint, it would be necessary either to buy new plexiglass or cut old plexiglass to the required dimensions.

The second solution to the situation was to double the plexiglass structure. Plexiglass would be attached to the aluminium frame (BOSCH) via auxiliary plates, slotted nuts, and screws. The advantage would be the creation of the second stage of fencing, which should protect the environment from a possible collision with the robotic arm.

The third variant provided deals with the doubling of plexiglass, and the two segments will be interconnected. The design will create a second part of the fence, independent, but at the same time connected to the first part, which will increase the strength of the primary glass and, if possible, make the glass become a stronger and more rigid unit.

2.2. Solution

The contracting authority had the decisive word for the approval of the final solution. The provided solution variants were subjected to a decision-making process by the customer. However, a few pitfalls arose concerning the implementation of the first variant, and the client disagreed with the dismantling of the assembled fencing. In the second variant of the solution, there was no connection between the first and second glass, which gave the impression that the added glass is only a kind of "second safety glass", which in essence may not be enough in the event of a possible collision.

The construction team agreed on the use of the change in the physical properties of the structure (TRIZ) by creating two segments of the protective fence and interconnecting them. The third variant was chosen for the solution using the TRIZ method, which gave us a strong solution to the technical conflict. A second glass was used, attached to the first using manufactured spacer rings (2), washers (3), nuts (1), and screws (4) (Figure 4).

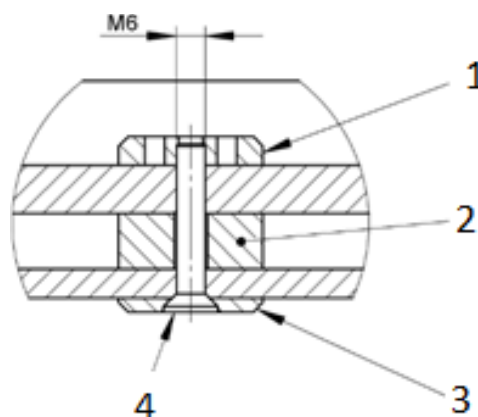


Fig. 4. Designed fencing reinforcement

To verify the data, and create the basis for the technical inspection, it was necessary to verify the proposed solution. The simulation took place in the Ansys Workbench program, addressed in the following section (Section 3).

3. CONSTRAINTS AND FEM SIMULATION

This section deals mainly with proving the effectiveness of solving the problem. Step one was the definition and modelling of design modifications, coming to new conclusions, and determining the key points of the design and possible variants of robot failure. The situation of the device is as follows:

- the device is bounded on three sides by insufficient fencing;
- two of these sides are large openable windows for possible maintenance;
- the filling consists of a 10 mm thick polycarbonate board;
- one side is a solid (non-openable) polycarbonate sheet.

The design team agreed to modify the equipment fencing as follows:

- adding spacer rings, nuts, washers, and screws to each endangered fencing wall and doubling the protection by adding another polycarbonate panel ($t = 6 \text{ mm}$);
- addition of security elements for locking the door (component made of polyamide PA6);
- prescription of the exact layout of individual spacer rings, locks, and hinges.

The simulation was performed in the Ansys Workbench program.

3.1. Forces locations

Within the design team, we wanted to determine the place of impact and the magnitude of the force as the most critical points of the structure, that is, where the given fencing elements will be most loaded. The most critical from this point of view was the centre of the largest wall of the fence and the edges of the opening doors Figures 5 and 6).

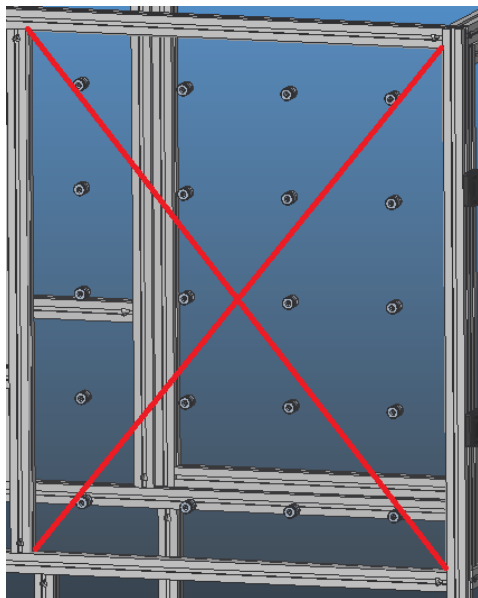


Fig. 5. Impact Glass (LH)

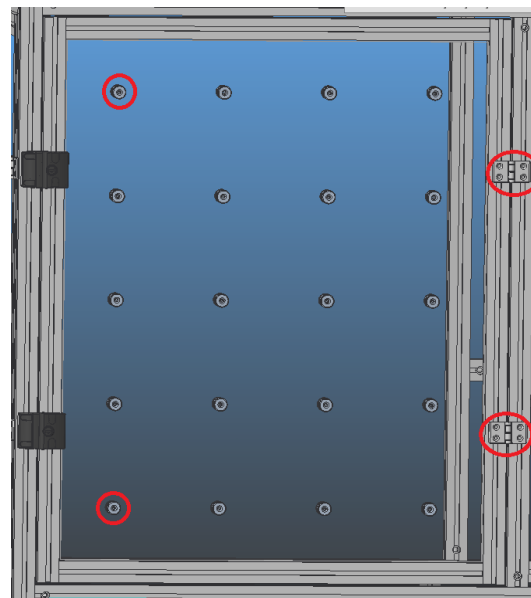


Fig. 6. Impact to distant opera points
(reaction in hinges)

The maximum load capacity can be read from the graph and from the data on the robotic arm [36] where the dependence of the distance of the centre of gravity of the robotic arm from the distance of the centre of gravity of the manipulated load is plotted. If we consider the problem as static, then we use the safety factor $k = 3$. If the arm is the most loaded, that is, with the largest possible manipulated load (7 kg), at max. distance $r = 0.24$ m, the force (formula 2) at the maximum speed on the axis J6 (12.566 rad / s) is as follows:

$$F_Z^{J6} = m * r * \omega_{J6}^2 \quad (1)$$

$$F_V = k * F_Z^{J6} = 795,838\text{N} \quad (2)$$

The resulting impact force at safety $k = 3$ could be obtained in the worst possible variant around 800 N when solved as a static problem. The simulation was performed only by loading the specified specific critical variants selected based on the previous risk analysis.

3.2. Forces on the side window (LH)

The method of impact can be seen in Figure 5, where the robotic arm would in the worst possible conditions, strike directly into the centre of the wall with the reinforcement already engaged. The centre of the polycarbonate plate from the edges of the Al profiles has the coordinates of the x-axis = 493.75 mm; y-axis = 596.5 mm.

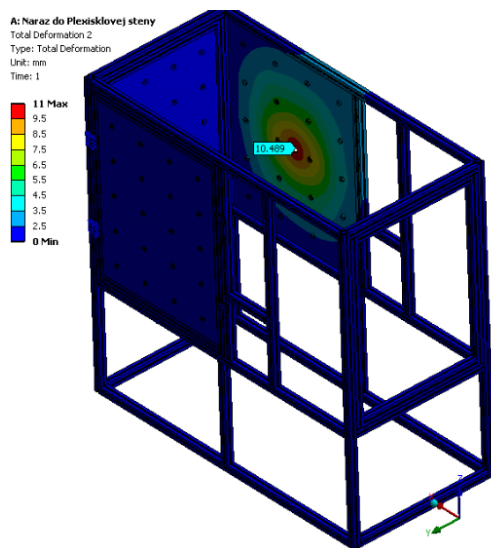


Fig. 7. Total deformation (LH)

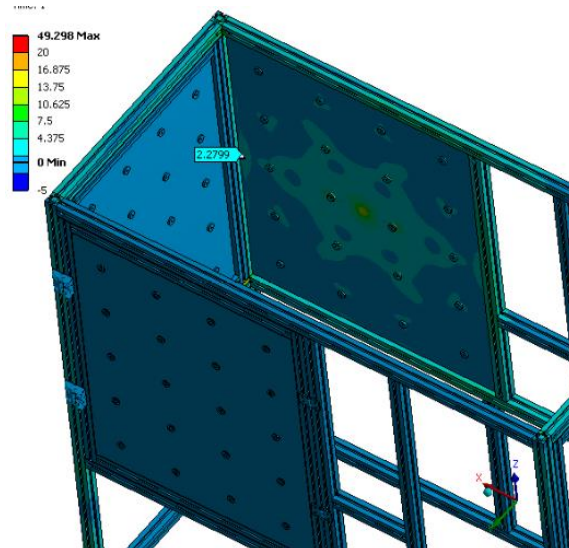


Fig. 8. Von Mises Stress (LH)

The resulting deflection and stresses on the largest side of the protective fence are still within the permissible stresses (49.3 MPa, Figure 8) because the maximum value of tensile strength for the polycarbonate board is 60 MPa (70 MPa) [37]. The deflection itself (Figure 7) is no longer large (11 mm) under the action of such a large force on such a large area with such a thick glass. The assumption that a given impact phenomenon occurs is small, with the robotic arm moving with much smaller loads during line handling.

3.2. Forces on the side door (RH)

In Figure 6, it is possible to see the critical points of application forces on the right side of the door. Hinges and locks are important parts as the fencing door must remain in place for safety, and protect its surroundings. Figure 6 shows possible points of collision within the RH side and are the centres of the spacer rings. With the correct placement, the impact in both variants should have approximately the same course, therefore, the variant of the impact into the upper spacer ring with the coordinates of the x-axis = 110.25 mm was chosen; y-axis = 981.7 mm (from the edge of the Al profile). The entire closing of the door on this side of the protective cage was solved using two locks made of PA6 and two hinges made of Al from BOSCH.

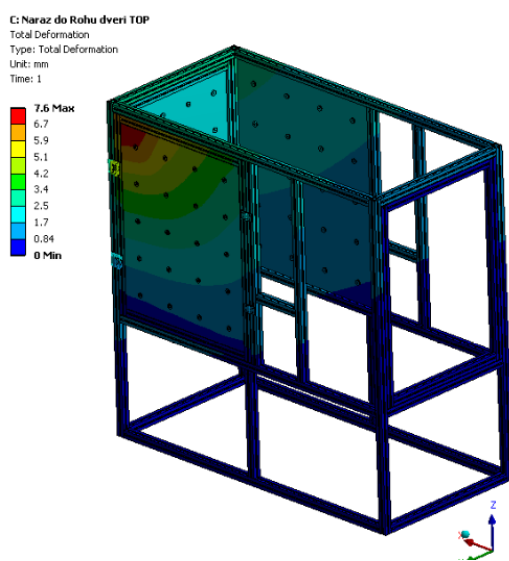


Fig. 9. Total deformation (RH).

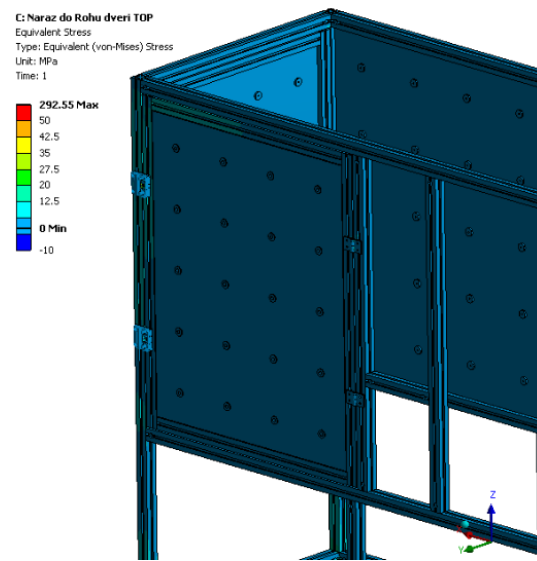


Fig. 10. Von Mises stress (RH)

In Figure 9, a maximum deviation of 7.6 mm was obtained, which is still at an acceptable value. According to the simulation, Figure 10 shows a voltage of 292.55 MPa, which is an unacceptable value. The given value, however, came out in the radii of the polyamide lock during the testing, which the FEM method can cause stress concentrators to form within the rounding (Figure 11). As for the reactions in the hinges, the largest reaction in the hinge came out as 400.5 N in Figure 15. The most stressed was the upper lock, which had the above-mentioned unacceptable value of von Mises voltage. The yield strength of polyamide PA6 is 76 MPa [38].

When using the FEM method, it is necessary to remove any rounding's, as this rounding's create stress concentration. Most of the lock component is coloured in a less pronounced green colour, which is a value of up to 47 MPa. The given value and the colouring of the whole part indicate that the given part (tongue) should withstand a possible collision with the robotic arm [39, 40]. The response in the lock was calculated in the simulation to the value of 824.23 N, which the lock bolts withstood in the verification calculation without major problems.

The simulation proved the necessary results for the certification of the device. The report was forwarded to the structural engineer for the safety assessment of the proposed fencing. The structural engineer affirmed the report, which was subsequently submitted to the technical inspection.

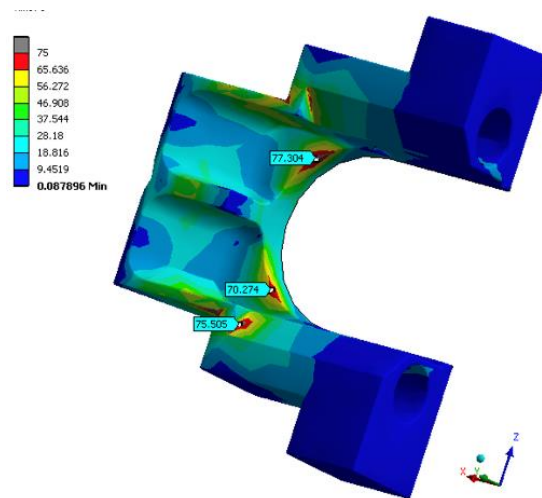


Fig. 11. The lock and von Mises Stress

4. CONCLUSION

The essence of this article was to introduce the reader to the solution to a security problem. In our case, a systematic approach and the use of one of the known innovative methods – TRIZ managed to get a suitable solution. The methodology is still used in large design offices, where the team of designers also have an expert in this methodology. The methodology can be used, not only for solving serious innovative tasks but also for various technical problems, where the solution lies in the correct definition of the problem. Further, this article gives an example of how the design team proceeded to design safer fencing.

As part of solving a specific problem of increasing safety, the team came up with a simple and effective solution to increase the strength of the fence, without much intervention. The provided solution was then simulated in the Ansys Workbench software, and certain conclusions were drawn from it. Based on these conclusions, a report was prepared for the structural engineer, who approved the results. Upon the conclusions drawn, the technical inspection evaluated the proposed solution as sufficient and, the equipment obtained a CE certificate after implementing the solution.

Source of funding

This study was supported by the Cultural and Educational Grant Agency MŠVVaŠ, under contract no. 015ŽU-4/2020 “Inovácie edukačného procesu s využitím nových technológií v CAD”.

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Received 08.02.2021; accepted in revised form 20.04.2021



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