Use of Virtual Reality to Facilitate Engineer Training in the Aerospace Industry

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Abstract. This work concerns automation of the training process, using modern information technologies, including virtual reality (VR). The starting point is an observation that automotive and aerospace industries require effective methods of preparation of engineering personnel. In this context, the technological process of preparing operations of a CNC numerical machine has been extracted. On this basis, a dedicated virtual reality environment, simulating manufacturing of a selected aircraft landing gear component, was created. For a comprehensive analysis of the pros and cons of the proposed approach, four forms of training, involving a physical CNC machine, a physical simulator, a software simulator, and the developed VR environment were instantiated. The features of each training form were analysed in terms of their potential for industrial applications. A survey, using the Net Promoter Score method, was also conducted among a target group of engineers, regarding the potential of use of each training form. As a result, the advantages and disadvantages of all four training forms were captured. They can be used as criteria for selecting the most effective training form.

Key words: virtual reality, industry 4.0, CNC machines, aviation industry, quality management.

1. Introduction

Virtual reality (VR) technology is relatively young, but it is rapidly developing. It involves creation of multimedia representations of objects, spaces, and events. Thus far, it has been used mostly in the entertainment industry [8, 16]. However, it is finding its way also to education [13, 14], culture [11, 17], or industry [1, 5], among others. With the increasing availability of VR devices, i.e. goggles/glasses, the space of its potential applicability is systematically increasing [19]. In this work, of particular interest is the use of VR in education, in the manufacturing industry in particular [15]. This mainly refers to employee training, to support familiarization with the tasks performed on the job.

Traditional training consists of two parts: theoretical and practical. In the industrial settings, the practical training can be carried on special stations, called trainers, which are (usually, not fully functional) production stations. They are used to emulate processes occurring on production lines. However, the final (advanced) training occurs using the actual equipment. Only then, it is possible to realistically verify the level of acquired skills, and familiarize the trainee with the specific details of a given process. Such traditional approach, in addition to obvious benefits, has significant drawbacks and limitations. First, the number of employees that can be trained simultaneously is restricted. Moreover, very often, such training involves removal of a device from the manufacturing process. Obviously, even when a partially functional machine is used as a trainer, this has associated costs. Furthermore, high costs are associated with consumption of materials used during training. Finally, use of actual machines, prevents testing critical scenarios, e.g. equipment malfunction, damages in the work-station area, operator errors, etc.

Therefore, use of VR technology in training seems very attractive. Specifically, VR (1) allows multiple repetition of test scenarios, without additional costs, (2) supports checking and verifying behaviour of the operator in various, also extreme, non-standard situations, and (3) allows simulating processes using diverse materials and processing tools. In this context, the advantages of VR are explored in the actual implementation of training of operation and programming of CNC machine tools, with the use case based on the needs of the aerospace industry. Here, it should be noted that in this industry, the precision manufacturing, using highly specialized tools, is a norm. Consequently, the equipment, and the tooling that comes with it, are particularly expensive. Moreover, training of CNC machine operators very often requires taking equipment out of production for an extended period (as it is too costly to purchase machine(s) just for teaching). Finally, observe also that, currently, employee mobility is high and will be higher in the coming years. As a result, it will be necessary to increase the frequency of dedicated training.

In this context it is easy to realize that VR can be, relatively easily, adapted to represent required training simulations. This makes it easy to train any person – new to CNC, or already skilled – to practice (repeatedly) the designed training path. However, in some areas, e.g. in dealing with highly accurate tools, materials, and products, VR can pose challenges. Since VR facilitates operations on 3D models, accuracy may be difficult to achieve for objects with complex structures, with edges and angles. Hence, the question can be asked, whether it is reasonable to apply VR to every field and process?

The need to address this question for aerospace industry is of particular importance in the Subcarpathian region of Poland, where an aerospace industry hub is located. Moreover, Rzeszow University of Technology trains many specialists for this industry. In this context, work aimed at developing and testing VR solutions for CNC machine operation training was undertaken. Accordingly, the main purpose of this contribution is to analyse usefulness of modern approaches to training CNC machine operators. In this context, an aircraft landing gear beam was chosen, as an example of a machined part.

Moreover, in addition to VR, training on an actual machine, training on machine simulator and using software simulator have been instantiated, to compare their effectiveness. To assess pros and cons of each approach, the NPS indicator was used. Finally, a set of recommendations concerning use of each training environment has been formulated.

2. Related work

VR technology is widely used in aircraft crew training and in ground handling. The scope and number of training sessions, directly affect the level of safety, and this aspect of air transport is the most important. Therefore, any innovation to streamline and raise efficiency and quality of training is in demand, and use of VR technology opens up new possibilities. However, because it is a relatively new technology, it still requires a lot of research, and testing, to achieve the needed level of efficiency.

In the aviation field, the first simulation systems were used to train pilots in the military. Studies showed that simulators reduced the flight training time, needed to achieve the required skills and competencies [15]. One of the important benefits of simulators is a very rapid feedback that allows analysis and elimination of undesirable behaviours. Here, a simple VR-based flight simulator that gives the perspective of flying in the air and allows interaction with the computer-generated environment, was presented in [18]. However, note that as early as 1993, potential role of VR-based flight simulators in training of civilian pilots was considered [20]. Moreover, the key features of virtual reality for industrial simulations were discussed. Interesting research, concerning training aircraft pilots, was presented in [3]. This work points to the need for appropriate adaptation of teaching materials and content to the technical requirements. Analysing literature related to pilot training, can be concluded that solutions based on VR not only reduce costs for flight schools but also provide a faster and more efficient learning process.

Another area of VR application in the aviation industry is the training of aircraft maintenance workers. Research reported in [9] discusses examples of VR and AR applications in the aviation industry, such as a VR training system for a Boeing 737. Specifically, VR was used to practice thrust reversal. Another example is a system capturing troubleshooting procedures for Airbus A320/A330 aircraft components [7]. Separately, VR is used to train employees of manufacturing companies. For instance, the Boeing Company, used VR and reduced employee preparation to just few weeks [4].

Of course, VR training of a workforce is gaining traction among manufacturers, and there are multiple dedicated solutions addressing needs of individual professions [6,12,21]. However, today there is no universal training platform for multiple industries, factories, or positions. Only narrow in scope systems with high potential to of cost and/or training time minimization are developed. Following this pathway, and recognizing the need for aviation industry workers training, a VR environment, for operating CNC equipment, was developed. Next its use and usability was compared with three other, popular,

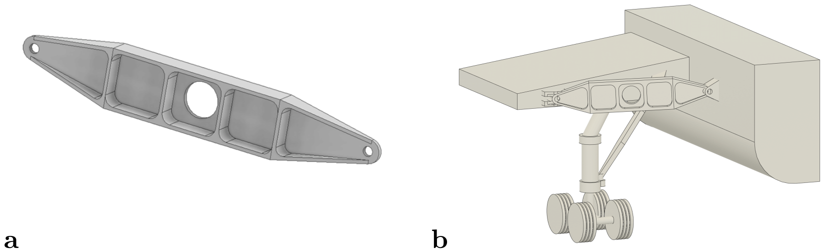

Fig. 1. (**a**) Example of an aircraft landing gear beam (simplified model). (**b**) A beam in full view of the aircraft landing gear.

approaches to worker training. Before proceeding to report gathered experiences, let us describe main assumptions guiding development of the VR system.

3. Preliminary assumptions

3.1. Technological process

Because of local interest in the aerospace industry, the aircraft landing gear beam was chosen as an example of a machined part. This beam is a structural part connecting the aircraft wing to the landing gear assembly. It works together with other landing gear components, e.g. a shock absorber. It is located in the wing, above the landing gear.

The landing gear beam, along with the landing gear itself, are subjected to considerable stress during aircraft landing. These parts are typically manufactured from aluminum and titanium alloys, due to the desired ratio of weight and strength. Figure 1 shows an example of a landing gear beam and its location in the landing gear, respectively. For VR representation of the training process, it was simplified to include only key machining operations needed to deliver the part. However, in the future, the "missing steps of the process" will be added to the application.

To make the part, it is necessary to consider the technological process, taking place during the manufacturing process (Fig. 2). Conceptualizing it, is the starting point for studying use of various forms of training for CNC machine operators. The captured information includes: change in shape, dimensions, physical and chemical properties, and surface quality of the workpiece, which take place as a result of operations to which it is subjected. Moreover, details concerning all necessary workshop aids, and steps needed to be completed is represented. The technological process was formulated on the basis of a detailed drawing of the part and in collaboration with the factory that actually produces such parts. The resulting process can be summarized as follows:

1. roughing and finishing milling of external surfaces,
2. roughing and finishing milling of internal surfaces,

3. spot drilling,
4. drilling,
5. threading.

In the next step, such factors as the workpiece material, the technological capabilities of the machine tool, and the production volume were also taken into account, when conceptualizing the technological process. The tool selection was carried out on the basis of the Gühring tool catalogues. Figure 3 shows the selected tools that have been used in the manufacturing process, represented in VR.

A block of material, measuring $302 \times 52 \times 23$ mm, made of aluminum alloy PA9/7075 (ISO AlZn5.5MgCu), was used (in the VR system) as a semi-finished part (element that is to be processed). The object was subjected to milling, drilling, drilling, and threading. Due to the prior preparation of the semi-finished product, to fit within tolerance dimensions, a single workpiece fixture was used. The semi-finished part was clamped in a vice (Fig. 4). The selection of tools and of the semi-finished product was

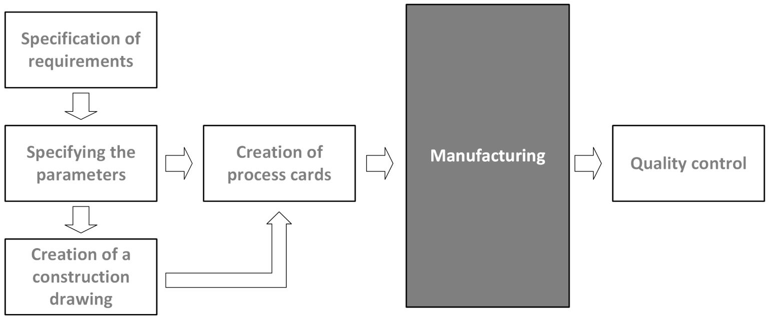

Fig. 2. The technological process.

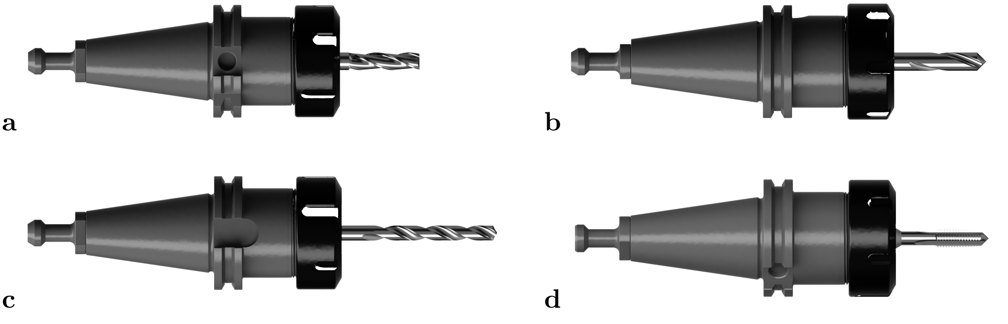

Fig. 3. Tools used in the VR environment: (**a**) endmill $\phi 10$, (**b**) NC spot drill $\phi 8$, (**c**) twist drill $\phi 8.5$, and (**d**) thread tap M10.

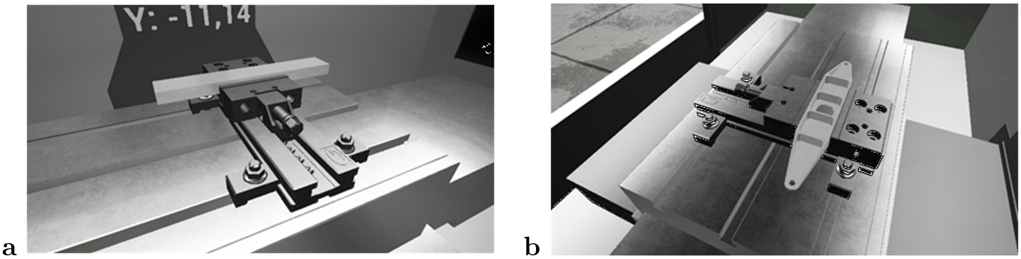

Fig. 4. Fabrication of aircraft landing gear beam in the VR environment: (**a**) mounting of the semi-finished product in a vice; (**b**) finished beam after the BV-represented fabrication process.

appropriately represented in the VR implementation, and all other forms, of training. In this way their usability could have been properly compared.

On the basis of the manufacturing drawing, and of the guidelines contained therein, and the information gathered from the manufacturer; process framework, process card, machining instruction sheets, machining sketch sheets, and tool setting sheets were prepared. According to the documentation, the machining of the part was programmed in the NX Siemens system. The resulting NC code, contains commands, needed to prepare the tool and to selects the cutting parameters. The NC code contains also coordinates of points along which setting and cutting movements are to be performed.

In the industrial practice, documentation prepared in this way, combined into a guide, becomes the input for the operator-programmer, producing the part on the machine tool. Specifically, to actually make the part, steps shown in Fig. 5 must be completed. Note that, each part, prepared (for instance, using the NX Siemens system) a similar documentation has to be prepared. This, in turn, can be used to instantiate any of the four training environments considered in this contribution.

Operations shown in Fig. 5 require the operator to know machine tool operation and programming. Specifically, execution of the correct tasks by the machine tool involves calling appropriate functions on the machine tool's control panel. Note that this can be correctly performed only by the trained operator.

3.2. Training forms

Four different forms of training, realizing the technological process described above, were considered: (a) physical Haas VF2 device, (b) physical simulator of the Haas device, (c) software simulator, and (d) dedicated VR environment (Fig. 6).

Available forms of training differ, depending on the tools used. (1) The first type of training is the most common form of on-site training. Moreover, it best reflects the actual conditions. However, most often, it requires taking the machine out of the production process. (2) In the case of the physical simulator, it is possible to learn the

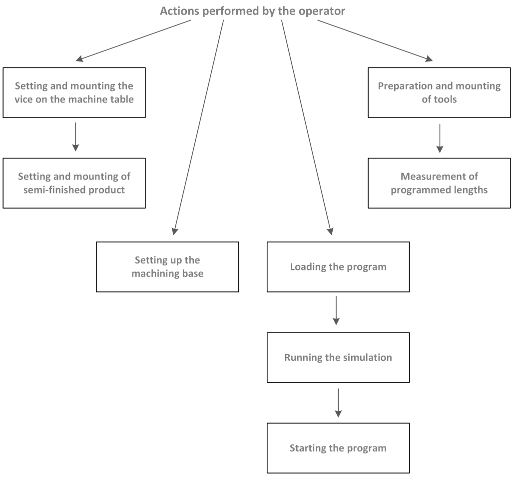

Fig. 5. Procedure for the preparation of the machining process on a numerical machine.

configuration and location of individual functions on a desktop that is identical to the machine tool. The disadvantage is the inability to observe commands being executed, due to lack of viewing devices, such as a monitor. (3) Software simulators are most popular in self-education. Note that, because of the relatively low prices (possibly existence of free simulators), self-training at home is also possible. Current software simulators, in addition to control panels, faithfully reproduce the body of the machine and simulate the movements and actions of the operator's command. (4) Since the last form of training is the focus of this contribution, it will be analysed in more details.

To compare the four forms of training, differentiated features were selected to provide a broader view of their potential. The selection of features is based on multiple years of experience, gathered by the research team in development and use of VR environments in didactic and engineering education. Table 1 summarizes the features that have been selected in the case of each form of training.

In the case of the first three forms of education, the time required to prepare the exercise tasks is relatively short. These activities usually involve preparation of a set of instructions, and technical documents that can be reused multiple times. The process of implementing training, based on simulation tools is the shortest, due to the flexibility of the simulators. The training performed directly on the CNC machine needs more time and attention for the teacher/instructor to prepare the machine and the raw materials. Moreover, instructor must carefully oversee what a student does. CNC machines are relatively "fragile" and this requires more commitment from the trainer, to avoid damages caused by student errors. Here, an adequate room, power supply, and safety

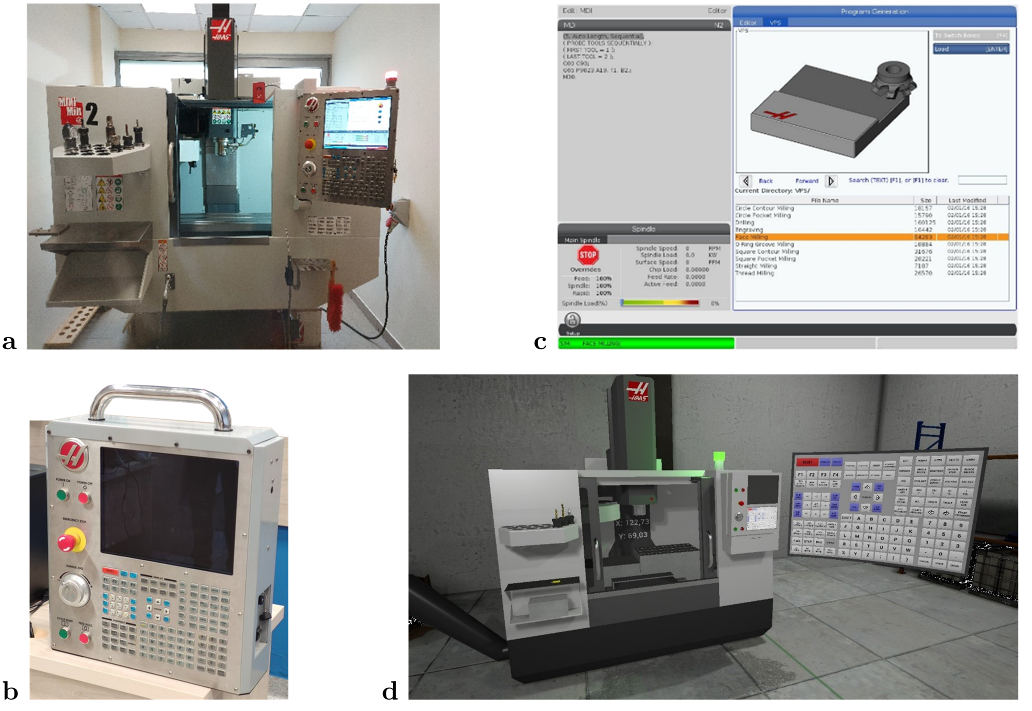

Fig. 6. Four potential training options: (**a**) a physical Haas machine; (**b**) a Haas simulator; (**c**) a computerized Haas simulator, and (**d**) a VR environment mimicking the Haas machine.

systems, need to be ensured during the instruction. In comparison, the hardest and the most time-consuming is the process for creating a VR training system. The virtual environment not only requires labour-intensive programming, but also (usually) includes 3D model design and implementation, as well as testing activities. This process involves also appropriate rooms, VR equipment and computers. However, most importantly, training of instructors who, by definition, are not IT specialists, is required. The aforementioned factors directly affect the cost of implementing each form of training.

Another important aspect, is the repeatability of exercises, which for organizational and cost reasons, can be limited for physical machines. The situation is different for simulators, which naturally facilitate repetition of specific exercises, without generating additional costs. Here, the VR environment, in which once-programmed training procedures can be repeated indefinitely, also compares very well. Note also that simulator and VR systems do not require consumable materials, further reducing costs of exercises.

The trainees' concentration during the class is also an important aspect of different

Tab. 1. A summary of the features of each form of education.

Feature/Potential	Physical machine CNC	Physical simulator	Software simulator	VR environment
Time-consuming task/exercise preparation	Low	Low	Low	High
The implementation process	Medium	Low	Low	High
Repetition of exercises	Low	Medium	High	High
Implementation costs	High	Medium	Low	Medium
Unit cost of exercise	High	Low	Low	Low
Concentrations during class	Low	Low	Medium	High
Hint system	Medium	Medium	Medium	High
Evaluation automation (grading)	Low	Low	Medium	High
Possibility of remote learning	Low	Low	High	High
Opportunities for self-education	Low	Low	High	Medium
Learning with a teacher	High	High	Medium	Medium
Need for additional training with a physical machine	Low	Medium	High	Medium
Risk of damage to equipment	High	Medium	Low	Low
Stress during training	High	Medium	Low	Medium
Training close to real conditions	High	Medium	Low	Medium
Training time	High	Low	Low	Low

forms of training. For the physical machine work, concentration is at a low level, because the operator starts the job and does not need to remain focused, when the physical fabrication can take a long time. Additionally, here, many factors can distract her, e.g. noise, other people, etc. Working with physical simulators is also not conducive to concentration. On the other hand, use of computer software forces a higher level of concentration due to the need to perform frequent, and deliberate, configuration activities, needed to achieve desired results. However, the highest level of concentration takes place in VR environments, and is caused by the immersion. This contributes to better learning results.

When analysing the prompting system, note that for physical machines, there is always an instructor next to the student. With simulators, there is one instructor for several students, while in the simulator and the VR environment, prompts are displayed by the systems when needed, while help from the instructor may be an extra option.

Another important aspect is that in the case of the physical machine and of the simulator, it is difficult, or even impossible, to automate the evaluation. Obviously, the instructor can look at the trainees' work during the exercises, but usually, the evaluation of work performance occurs at the end of the work, or after the completion of major milestones. In the case of the computer simulator, progress at various stages of the task can be evaluated, while in the VR environment, performance can be evaluated in real-time.

Separately, let us note that modern teaching processes largely take into account the possibility of implementing remote learning. This is due to the dispersion of trainees, cost reduction, time flexibility, and external factors such as pandemics or weather conditions. Recent years in particular (prompted by the COVID-19 pandemics) made it clear that remote learning can be implemented effectively, even on a large scale. Therefore, it is also necessary to look at this aspect of education. Of course, due to the way the physical machine is operated, it is not possible to use it directly for remote education, including general instructional courses. The situation is similar to physical simulators, as they were designed for direct access by trainees. Computer simulators, on the other hand, can be used anywhere and anytime, on local and remote computers. In this context, it might seem that VR systems are dedicated to desktop learning. However, nowadays, the cost of purchasing simple VR systems continues to decrease, making them accessible to a large audience, who, thanks to the Internet, can access repositories of VR applications. Furthermore, VR allows one to work remotely with an instructor. This brings about possibility of self-learning. However, it should be admitted that as of today, use of VR technology may require cooperation of the instructor.

The nature of solutions, based on physical equipment, is that there is always a risk of damage to the machinery through carelessness, misuse, or simple failure. In contrast, computer software reduces such risks to almost zero. However, any mistakes, made by the user, can result in the need to start work from the scratch or, in the worst situation, to restart the software, or the system. Nevertheless, devices modelled in the VR environment cannot be physically damaged by the user. However, the potential risk is the possibility of damaging the VR goggles and/or the manipulators. Another aspect of use of particular forms of training, also related to the possibility of damage to the machinery, is the possible stress on trainees. From this perspective, working on the physical equipment can involve much higher level of stress than use of computer software. The awareness of the consequences of mistakes, made during exercises, in terms of the equipment, consumables, or one's own health, may result in stress and lack of comfort in some trainees. However, VR technology can create also a certain level of discomfort, this time caused by working in a virtual environment.

Analysing various forms of training, it can be concluded that solutions based on hardware platforms, by definition, provide an environment that is closer to real working conditions than computer software. On the other hand, in the VR environment it is possible to relatively well reproduce the real working conditions. Nevertheless, as of today, the technology still has some limitations related to the reproduction of physical phenomena, and involves simplifications and generalizations, necessary when creating a VR environment. However, an advantage of working with computer systems and software is the ability to speed up certain processes that, in reality, take substantial amount of time. Therefore, such forms of training allow more efficient use of available training time.

Usually, after machine operators have finished training, there is a need for additional bench training at the target manufacturing machine. However, when training with a physical CNC machine, it is often identical to the actual workstation (or from the same series). This minimizes the need for additional training. In the case of a real simulator, use of an actual control system is involved. However, the specifics of manufacturing of the parts, their attachment, tool wear, etc., cannot covered. Here, additional training is needed, with particular emphasis on manual handling of manufacturing elements of the device. In computer simulators, trainees learn the process of numerical preparation of parts for manufacturing, but the visualization of the machining control process, on the device's manipulator, may be limited (e.g. a universal manipulator may be used). Here, the training on the actual equipment is needed, and must take into account the specific CNC equipment that is to be used. Finally, VR training combines elements from the remaining approaches. Here, one can accurately replicate all work scenarios that operators may encounter in the real world. VR training is followed by training in a real environment, focused primarily on improving manual skills and taking into account, for example, the weight of individual components and the specifics of their assembly (e.g., the torque of individual components).

In summary, it can be concluded that each form of training has its pros and cons. Each solution requires a repetitive approach, as engineers learn through practice. Here, the VR-based solution can be naturally adjusted to any training at any facilities. What is needed is a team of programmers/graphics designers and testers to create an environment ready for the company needs. Therefore, it was deemed important to compare side-by-side actual realizations of each of the four training approaches and verify the, above stated, expectations, with reactions of actual trainees.

4. Survey of participants' opinions on selected forms of education

As mentioned above, a survey has been performed on the group of random participants with and without knowledge of using the CNC machine. To analyse results the NPS indicator has been used with additional A Mann–Whitney U test.

4.1. The research process

In order to verify and analyse the working hypothesis, an anonymous survey was administered to a group of 25 respondents in 2022. A survey questionnaire was made available through the CAVI (Computer Assisted Web Interview) and PAPI (PAper and Pencil Interview) methods [22]. During the survey, no personal data was collected. Moreover, both CAVI and PAPI were set in such a way that the collected information has been fully anonymized. The questionnaire targeted a group of engineers after they tested each of the four methods. Then the respondents were asked to answer questions related to:

1. working and learning with a physical CNC machine,
2. working and learning with a physical simulator,
3. working and learning with the use of a software simulator,
4. working and learning with the VR system.

The questionnaire included closed and open-ended questions. The questionnaire also used a metric that asked respondents to specify gender information, as well as experience with VR systems, CNC machines, and simulators. The NPS indicator was also used to examine the extent to which respondents are willing to promote the selected forms of education in their environment. STATISTICA 13 was used to analyse the data. The statistical analysis primarily used count tables, which showed both numerical and percentage summaries of individual responses, and used the arithmetic mean and coefficient of variation (denoted as v). The coefficient of variation is the ratio of the standard deviation to the mean. The following assumptions were made: when $v < 25\%$ – there is low variability, $25\% \leq v < 45\%$- there is average variability, $45\% \leq v \leq 100\%$ – there is strong variability, $v > 100\%$ – there is compelling variability. Responses to open-ended questions on the main advantages and disadvantages of using selected forms of education were categorized and presented graphically in the order of the most frequent responses. The Mann–Whitney U test was used to determine the relationship between qualitative and quantitative characteristics. The study was conducted at a significance level of $\alpha = 0.05$. According to the literature, it was assumed that: when $p < .05$ – there is a statistically significant relationship; $p < .01$ – there is a highly significant relationship; $p < .001$ – there is a very high statistically significant relationship [2, 10].

4.2. Analysis of survey results

The structure of the set of respondents by gender is shown in Tab. 2. The data indicates that the survey group is predominantly male – 88%. In contrast, 12% of the respondents were women. Another question in the survey-concerned respondents' experience with VR environments. Analysing the data, it can be concluded that 92% of respondents have used such solutions in the past. In contrast, 8% of the respondents had no exposure to VR systems. Respondents' experience with physical CNC machines was further considered in the survey. 76% of the respondents confirmed their experience. Nearly one in the four respondents had not operated CNC machines in the past. Another question in the survey concerned the experience of the use of simulation applications. As in the case of CNC machines, 76% of the respondents were familiar with such solutions. In contrast, 24% of respondents to this question answered negatively. Table 2 also presents detailed data on respondents' experience with selected forms of training. According to the survey, 68% of respondents have experience with CNC machines, simulators, and VR environments.

Tab. 2. Characteristics of the respondents.

Variable	N	%
Gender		
Male	22	88%
Female	3	12%
Declaration of experience with the VR environment		
Yes	23	92%
No	2	8%
Experience of work with physical CNC machines		
Yes	19	76%
No	6	24%
Experience of use of simulation applications		
Yes	19	76%
No	6	24%
Form(s) of education		
Experience with a physical CNC machine, simulators and VR environment	17	68%
Experience in operating in a VR environment	6	24%
Experience in operating a physical CNC machine and simulators	2	8%

On the other hand, 24% of respondents have only used VR systems before. Experience in operating a physical CNC machine and simulators was declared by 8% of respondents.

Based on the collected research material, an evaluation of selected education forms was conducted (Tab. 3). According to the survey, respondents for each type of training mostly believe that additional training is needed. However, the largest group of trainees (72%) believe that additional training should be provided in the case of using VR systems. In contrast, 28% of trainees believe that further training is not necessary in this case. Considering the results obtained in the area of the computer simulator, 68% of respondents gave an affirmative answer, and one in three respondents believed that additional training is not necessary. More than half (56%) of the respondents declare the need for additional classes related to the operation of the physical simulator, and 44% of respondents have no opinion. The need to organize additional classes on the operation of the physical CNC machine is stated by 48% of the trainees, 12% believe it is not necessary, and 40% of the respondents have no opinion on the subject.

When asked about the clarity and comprehensibility of the defined tasks, respondents in each case mostly answered affirmatively. The VR environment received 84% positive responses, working with a physical CNC machine and a physical simulator each received 80% affirmative responses, and the use of a software simulator received 76% affirmative responses. Among the respondents, there was no person who negatively evaluated this aspect of learning.

According to the respondents, each listed training course supports application of the acquired knowledge in practice, with the greatest opportunities provided by exposure to a physical CNC machine (88% of positive responses), the VR environment (72% of respondents answered affirmatively), and use of a physical simulator (68% of respondents). The use of a software simulator received 64% of the positive responses.

Understanding practical aspects of operating a CNC machine tool is possible by using a physical machine (100% of positive responses), as well as the use of a VR environment (80% of affirmative responses). In the case of the use of a software simulator, this was confirmed by 52% of respondents, and 68% of respondents in this aspect positively evaluate the use of a physical simulator, 8% expressed themselves negatively, and 24% have no opinion on the subject.

In the next part of the survey, the possibility of achieving the expected learning outcomes during the implementation of the selected training courses was verified. The data indicate that, according to the respondents, the greatest opportunities in this aspect are provided by working with a physical CNC machine (92% of affirmative responses), as well as the VR environment (88% of positive responses). The realization of the established learning objectives when using a software simulator is declared by 60% of the trainees. On the other hand, 44% of respondents believe that it is possible in the case of using a physical simulator, and 4% of respondents believe that it is impossible to achieve the assumed learning outcomes during this form of training.

According to respondents, the availability of the necessary functionalities needed to perform tasks to the greatest extent is possible by using working with a physical CNC machine (100% confirm such possibilities), as well as in a VR environment (72% of respondents gave an affirmative answer). 44% of respondents declare the usefulness of a physical simulator in this area, and only 28% of respondents positively evaluated the use of a software simulator in this aspect.

Another question in the survey concerned the ability to replicate real manufacturing processes. According to respondents, the greatest potential in this regard is working with a physical CNC machine (88% of respondents gave an affirmative answer, 12% have no opinion), as well as working in a VR environment (72% of respondents confirm such possibilities, 28% have no opinion). The use of a software simulator is viewed positively in this aspect by 44% of respondents, but 40% gave a negative answer. Nearly one in five respondents believe that working with a physical simulator does not allow them o reflect real manufacturing processes, 16% confirm such possibilities, and 60% of respondents have no opinion on this issue.

The data allow one to conclude that the possibility of cooperation and exchange of experience occurs to the greatest extent when participating in training using VR solutions (96% of affirmative answers, 4% have no opinion), as well as when working with a physical CNC machine (80% of affirmative answers, 20% of negative answers). Analysing the data for software simulator users, the possibility of cooperation is declared by 60% of respondents, 36% gave a negative answer, and 4% of trainees had no opinion. In the case of working with a physical simulator, 44% of respondents believe that this form of training gives the possibility of exchanging knowledge and experience with others, 8% believe that this is impossible, and 48% of respondents have no opinion on the subject.

Based on the cited data, it can be concluded that the necessity of repetition is most prevalent in the case of training with a physical simulator (76% of respondents gave an affirmative answer, 24% are negative answers), as well as a computer simulator (76% of respondents confirmed this necessity, 24% of trainees have no opinion). In the case of working with a physical CNC machine, 48% of users believe that repetitive exercises are necessary, whereas 52% of respondents have no opinion. Analysis of the data for the VR environment showed that 40% of respondents confirm the necessity of additional classes, whereas 60% of respondents have no opinion on the subject.

According to respondents, the most time-consuming form of learning is training with a physical CNC machine (80% of respondents answered in the affirmative, and 12% of respondents gave a negative answer). 56% of trainees declared that learning with a physical simulator requires a considerable amount of time, while 16% of respondents believe that it is not necessary. On the other hand, similar results in the evaluations of respondents who received training using a software simulator and VR environment, where 64% of respondents believe that these forms of training are not time-consuming.

The data allow us to conclude that the most activating and engaging for the trainee during the class is learning using the VR environment – 100% of respondents declare involvement during this form of training. Slightly more than half of the respondents (52%) confirmed active participation while working with a physical CNC machine, while 48% had no opinion on the subject. In the case of using a software simulator, 44% of respondents stated that they are active during classes, whereas 40% gave a negative answer. The high involvement during classes with the physical simulator is confirmed by only 28% of respondents, 44% have no opinion, and 28% of trainees answered in the negative.

The survey further verified the need for other forms of training in the area of CNC machine operation. Among the respondents, the greatest need for other additional training is in the case of the use of the VR environment (76% of respondents declare the need to organize other forms of learning, 4% of respondents answered in the negative) and software simulation (72% of respondents answered in the affirmative, and 4% of trainees think it is not necessary). The necessity of other forms of learning in the case of training with the use of a physical CNC machine is declared by 32% of respondents, 60% have no opinion, and 8% of respondents answered in the negative. Analysing the results obtained

Tab. 3. Evaluation of selected forms of education.

Question	Response	CNC machines	Physical simulator	Computer simulator	VR system
Does this form of education require additional training?	Definitely yes	28%	0%	0%	12%
	Yes	20%	56%	68%	60%
	Difficult to say	40%	44%	0%	0%
	No	12%	0%	32%	28%
Were the tasks to be carried out defined in a clear and understandable manner?	Definitely yes	20%	8%	0%	40%
	Yes	60%	72%	76%	44%
	Difficult to say	20%	20%	20%	12%
	No	0%	0%	4%	4%
Does this form of training allow you to use the acquired theoretical knowledge?	Definitely yes	64%	8%	0%	24%
	Yes	24%	60%	64%	48%
	Difficult to say	12%	28%	32%	20%
	No	0%	4%	4%	8%
Does this form of education allow you to understand the practical aspects of operating CNC machine tools?	Definitely yes	80%	4%	0%	32%
	Yes	20%	64%	52%	48%
	Difficult to say	0%	24%	44%	12%
	No	0%	8%	4%	8%
In your opinion, does this form of education achieve the desired learning outcomes?	Definitely yes	80%	0%	0%	40%
	Yes	12%	44%	60%	48%
	Difficult to say	8%	52%	40%	8%
	No	0%	4%	0%	4%
In your opinion, did this form of education provide access to all the necessary functionalities needed to perform the tasks?	Definitely yes	60%	4%	0%	12%
	Yes	40%	64%	28%	60%
	Difficult to say	0%	24%	64%	20%
	No	0%	8%	8%	8%
Does this form of education fully replicate the actual manufacturing processes?	Definitely yes	40%	0%	0%	12%
	Yes	48%	16%	44%	60%
	Difficult to say	12%	60%	16%	28%
	No	0%	24%	40%	0%
Does this form of education enable collaboration and exchange of knowledge and experience with others?	Definitely yes	12%	0%	16%	28%
	Yes	68%	44%	44%	68%
	Difficult to say	0%	48%	4%	4%
	No	20%	8%	36%	0%
Does this form of education require repeated exercises to acquire the required?	Definitely yes	0%	0%	28%	12%
	Yes	48%	76%	48%	28%
	Difficult to say	52%	0%	24%	60%
	No	0%	24%	0%	0%
In your opinion, is this form of education time-consuming?	Definitely yes	8%	0%	0%	0%
	Yes	72%	56%	36%	28%
	Difficult to say	8%	28%	0%	8%
	No	12%	16%	64%	64%
Does this form of education most activate and engage during classes?	Definitely yes	20%	0%	16%	84%
	Yes	32%	28%	28%	16%
	Difficult to say	48%	44%	16%	0%
	No	0%	28%	40%	0%
Does this form of training also require the use of another form of training in the area of CNC machine operation?	Definitely yes	20%	0%	28%	12%
	Yes	12%	28%	44%	64%
	Difficult to say	60%	72%	24%	20%
	No	8%	0%	4%	4%
Is this form of education adequate for training a team of engineers for the aerospace industry?	Definitely yes	68%	0%	0%	36%
	Yes	24%	36%	44%	44%
	Difficult to say	8%	44%	56%	16%
	No	0%	20%	0%	4%
Was the level of support from the system/software/device enough?	Definitely yes	0%	12%	20%	44%
	Yes	72%	36%	40%	56%
	Difficult to say	20%	28%	36%	0%
	No	8%	24%	4%	0%
Did you feel comfortable completing tasks using this form of education?	Definitely yes	0%	0%	16%	76%
	Yes	60%	52%	76%	24%
	Difficult to say	40%	48%	8%	0%
	No	0%	0%	0%	0%

in the area of training with the use of a physical simulator, it can be concluded that the majority of respondents (72%) have no opinion on the subject, and 28% believe that there is a need to organize additional forms of learning.

Another question in the survey concerned the appropriateness of using selected forms of training to teach engineering personnel for the aerospace industry. Thus, analysing the data, it can be concluded that in this case, the trainees most prefer training using a physical CNC machine (92% of affirmative responses), as well as VR (80% of positive prompts). 44% of respondents consider the appropriateness of using a software simulator. 36% of respondents recommend the use of physical simulators, while one in five trainees do not recommend this form of training.

The survey further analysed the level of support from the system/software/device. As can be seen from the data in Tab. 3 in this aspect, the highest rating was given to the VR environment (100% of positive responses), followed in order by the use of a physical CNC machine (72% of affirmative responses, 8% of negative responses), working a software simulator (60% of positive responses, 4% of negative responses), and the use of a physical simulator (48% of affirmative responses, 24% of negative responses).

The level of comfort during training is highest when working with VR systems (100% of positive responses). High comfort was also declared when using a software simulator (92% of positive responses). 60% of respondents confirmed comfort when using a physical CNC machine. On the other hand, 52% of trainees confirmed comfort when training using a physical simulator.

4.3. NPS indicator survey

In the following part of the questionnaire, respondents were asked to answer the following question, "How likely are you to recommend this form of training for learning to operate CNC machine tools?" The question was constructed based on an 11-point scale, where the number 0 – I would definitely not recommend this form of training, while the number 10 – I would definitely recommend this form of training. Table 4 shows the aggregate results of the analysis.

Analysing the results, the following conclusions can be drawn:

- The highest NPS rates are found for training with the use of a physical CNC machine (84) and VR systems (76), indicating a high degree of satisfaction with participation in this type of training.
- The NPS rate for software simulator training was 24, which is below the satisfaction level.
- Considering the results for physical simulator training, it turns out that among the respondents there were no people who could confidently recommend this type of training. Thus, after determining the difference between the percentage of promoters (0%) and detractors (56%), it turns out that the NPS rate, in this case, was −56.

Tab. 4. Summary results of the NPS analysis.

Feature/Parameters	Physical CNC machine	Physical simulator	Software simulator	VR environment
Promoters	84%	0%	44%	76%
Passives	16%	44%	36%	24%
Detractors	0%	56%	20%	0%
NPS	84	−56	24	76
Average	9.12	6.44	7.60	9.08
Coef. of variation	9.66	18.53	20.45	8.36

- The highest arithmetic average is in the case of training with the use of a physical CNC machine – 9.12, followed, in turn, by training using VR systems – 9.08; training using a software simulator – 7.6; training using a physical simulator – 6.44.
- The coefficient of variation for the study variables was as follows: training with a physical CNC device – 9.66; training with a physical simulator – 18.53; training with a software simulator – 20.45; training with the use of a VR system – 8.36. These results indicate low variability in the responses to the question asked.

4.4. Verification of the stated hypotheses

Taking into account the results of the surveys presented in section IV.B and C, this article attempts to verify the following research hypotheses:

- it is assumed that experience with the VR environment does not affect the propensity to promote selected forms of education in the environment,
- it is assumed that experience with a physical CNC machine does not affect the propensity to promote selected forms of education in the environment,
- it is assumed that experience with simulation applications does not affect the propensity to promote selected forms of education in the environment,
- it is assumed that gender does not affect the propensity to promote selected forms of education in the environment.

A Mann–Whitney U test was used to assess the relationship between quantitative and qualitative characteristics. The first part of the study tested whether experience with a VR environment influenced the propensity to promote selected forms of education in the environment. The same tests were conducted for the experience with physical CNC machines and the experience with simulation applications. In each case, the test probability p was higher than the significance-level $\alpha = 0$, adopted for the study (Tab. 5, Tab. 6 and Tab. 7). This means that this relationship does not exist.

In the next part of the study, it was decided to test whether gender impacts the

Tab. 5. Results of research on the impact of experience with VR systems on the propensity to promote selected forms of education.

	p
Willingness to promote training with a physical CNC device	0.1763
A tendency to promote training using a physical simulator	1.0000
The tendency to promote training using a software simulator	0.8023
Willingness to promote training with the use of the VR system	0.0639

Tab. 6. Results of research on the impact of experience with physical CNC machines on the propensity to promote selected forms of education.

	p
Willingness to promote training with a physical CNC device	0.5455
A tendency to promote training using a physical simulator	0.3227
The tendency to promote training using a software simulator	0.2391
Willingness to promote training with the use of the VR system	0.7991

propensity of respondents to promote selected forms of education in their environment (Tab. 8). The described results with a test probability-level p and the adopted significance-level $\alpha = 0.05$ allow us to accept the null hypothesis. Thus, the value of the Mann – Whitney U tests allows us to conclude that the propensity to promote selected forms of education does not depend on gender. Additionally, the data in Fig. 7 allow us to conclude that the average grade scores obtained in the various groups studied differ slightly.

4.5. Advantages and disadvantages of using selected forms of education

In open-ended questions, respondents were asked to provide their opinions on the benefits as well as drawbacks of using the selected forms of training. When analysing the results,

Tab. 7. Results of research on the impact of experience with simulation applications on the propensity to promote selected forms of education.

	p
Willingness to promote training with a physical CNC device	0.5455
A tendency to promote training using a physical simulator	0.3399
The tendency to promote training using a software simulator	0.2391
Willingness to promote training with the use of the VR system	0.7991

Tab. 8. Results of research on the effect of gender on the propensity to promote selected forms of education.

	p
Willingness to promote training with a physical CNC device	0.8344
A tendency to promote training using a physical simulator	0.7442
The tendency to promote training using a software simulator	0.8671
Willingness to promote training with the use of the VR system	0.1949

the respondents' answers were categorized and presented in the order of the most frequent responses. Table 9 shows the summary results of the analysis regarding the benefits of using selected forms of training.

According to the survey, the most common answer regarding the benefits of training with a physical CNC machine is the ability to replicate real manufacturing processes,

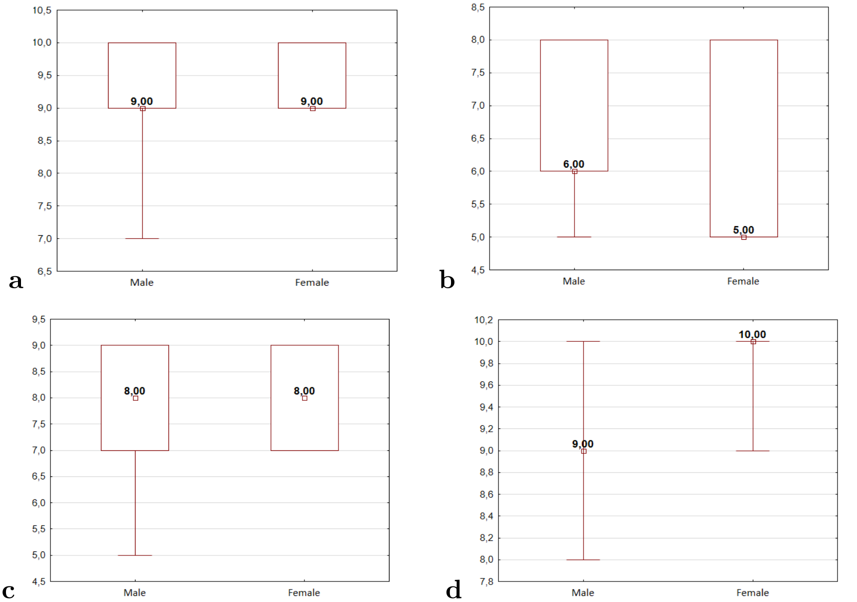

Fig. 7. Evaluation of selected forms of education by gender. Questions for which the graph were made: (**a**) How likely is it that you would recommend training with a physical CNC machine as a form of learning how to use CNC machine tools? (**b**) How likely is it that you would recommend a physical simulator to learn how to use CNC machine tools? (**c**) How likely is it that you would recommend computer simulators to learn how to use CNC machine tools? (**d**) How likely is it that you would recommend VR systems for learning how to use CNC machine tools?

Tab. 9. Respondents' opinions on the benefits of using selected forms of education.

Variable	N	%
CNC machines		
The ability to replicate real manufacturing processes	19	76%
The ability to recognize the behaviour and functionality of the CNC machine	15	60%
Physical simulator		
Reduction in costs associated with the purchase of a CNC machine	16	64%
No possibility of damaging the CNC machine	14	56%
Introduction to working with a CNC machine	9	36%
Possibility to train many people at the same time	7	28%
Software Simulator		
Possibility of remote learning	15	60%
The ability to run the simulator on any computer at any time	8	32%
VR System		
High interactivity	21	84%
An immersive approach to the manufacturing process and the use of the CNC machine	18	72%
The modernity of the applied technologies	12	48%
Low training costs	10	40%

which allows the recognition of machine tool behaviour and functionality. Respondents, therefore, pointed to the opportunity for the trainee to acquire practical skills and qualifications to perform the tasks of the operator's position.

In the case of using a physical simulator, respondents listed the reduction in costs associated with the purchase of a CNC machine among the main advantages. Another benefit is that there is no possibility of damaging the machine, which is especially important for trainees who are just starting out, thus significantly increasing their comfort level. Training with the use of a physical simulator also allows for the possibility of teaching many people simultaneously, which was also mentioned by respondents.

According to the respondents, the main advantage of training using a software simulator is the possibility of remote learning, which allows the exercises to be carried out at any time and place. Note that until recently, the form of remote learning was used mainly as a solution for further training and improving professional skills. Currently, it is a way of education, which is steadily gaining in popularity due to its benefits. This is because it allows individualization of the learning process, as well as reducing time and costs associated with travel or temporary accommodation.

Among the benefits of using VR systems, respondents mentioned, first, high interactivity, which allows active participation in the training, and an immersive approach, thanks to which the trainee assimilates knowledge more effectively and remembers the information directed to him. Respondents also pointed out that the VR environment is counted among the modern technologies included in Industry 4.0, which makes this training very attractive to development-oriented engineers. Respondents also point to the low cost of implementing training in a VR scenario, as through this type of training companies reduce investments related to the purchase of machinery. This perception of VR technology may be appropriate from the viewpoint of those being trained. However, preparing VR simulations, machine tool models, and scenarios is a time- and cost-intensive process. Once a full training scenario is prepared in a VR environment, it scales very well, however, because the preparation of each successive training station comes down to the purchase of the actual computer and VR glasses, which is many times cheaper than buying a new CNC machine. Therefore, it can be said that in the case of preparing a single CNC and VR workstation, the costs are similar but as the number of workstations increases, the CNC costs increase linearly, while in the case of VR, they only involve the purchase of further relatively inexpensive VR sets. In this model, leasing models of VR infrastructure along with models of VR environments for training implementation are also increasingly popular, which can further reduce the cost of VR training.

The last question in the survey concerned the disadvantages associated with the use of the selected forms of education. The results of the analysis are shown in Tab. 10.

The analysis of the collected material shows that in the case of training with a physical CNC machine, respondents listed the need for physical access to the machine and the possibility of damage to the machine tool among the biggest risks. Thus, there is a concern among respondents that their inexperience could affect the creation of errors, and thus incur costs to the company for repairs.

According to the respondents, the main drawbacks of using physical simulators are the inability to replicate real manufacturing processes, which do not allow to recognize the behaviour and functionality of the CNC machine. As a result the lack of contact with physical equipment and an immersive approach are the main drawbacks of using software simulators, according to respondents.

Respondents' concerns about the use of a VR environment again primarily included the lack of contact with a physical machine. Thus, it can be concluded that for the trainees, it is critical to replicate real manufacturing processes and to be able to interact with the machine. Another threat that respondents presented is the need for a large amount of space. Respondents also pointed out that the use of the VR environment can cause side effects such as eye pain. However, this aspect of using VR technology is very subjective, and some users may experience negative effects from being in VR, while others may not.

Tab. 10. Respondents' opinions on the disadvantages of using selected forms of education.

Disadvantages	N	%
CNC machines		
The need for physical access to the machine	15	60%
Possibility of damaging the machine	13	52%
Long waiting time for delivery/access to the machine	9	36%
The need for continuous supervision of trainers (physical presence)	7	28%
The need to have a base of premises where the machines will be located, including adequate strength of ceilings and noise	5	20%
Cost of consumables and artefact materials	4	16%
Physical simulator		
Lack of the ability to replicate actual manufacturing processes	19	76%
Inability to recognize the behaviour and functionality of the CNC machine	12	48%
Need to own/purchase specialized simulation dashboards – long waiting time for delivery	6	24%
The versatility of dashboards – differences between real dashboards and those in physical simulators	4	16%
Software Simulator		
No contact with physical equipment	19	76%
Not a very immersive form of learning	12	48%
Lack of possibility to develop manual skills to operate a particular machine	4	16%
VR System		
No contact with the physical machine	20	80%
Necessary to have a large amount of space	9	36%
Discomfort in using VR glasses related to eye pain and weight of glasses, pressure on the head	7	28%
Dizziness and vagal problems	4	16%
No physical sensation of the weight of the parts in question, the pressure force when inserting the tool, etc.	3	12%

5. Conclusion

The rapid development of industry, especially in the fields of aviation and automotive industry, requires the implementation of modern methods and means to support manufacturing processes. One of the basic elements of the manufacturing process is the preparation of operators of digital machines, including CNC. Classic training methods tend to be time-consuming and costly. Moreover, in the case of extraordinary situations such as epidemics, natural disasters, etc., personnel preparation cycles can be interrupted, resulting in a significant disruption in the schedule of preparation and implementation of production processes. In particular, the SARS-CoV-2 epidemic period has made everyone aware of the importance of alternative solutions that were not commonly used before. One such solution is the possibility of using a virtual reality environment to automate various processes, including the training.

In this paper four approaches to training engineering personnel in the operation of CNC equipment are compared and analysed. One of them is a novel solution based on VR technology. Given the complexity of manufacturing components, for the aerospace industry, in particular, the process of manufacturing a specific component of an aircraft landing gear is presented. Due to the high-quality requirements of such components, the process of preparing a team of operators must guarantee a high level of quality. This, in turn, involves ensuring the repetition of training procedures and activities. As a result, their cost and the time required to conduct them increase. The results show that using an appropriate VR environment can be very useful for training specialists in the area of for example operating the CNC machine. Based on results many participants chose VR over other simulations as a good solution for training.

Studies conducted indicate great potential for the use of VR technology in the industry. Of course, this work refers only to one specific application. As it was mentioned before a practical approach is better then theoretical in many ways. By using physical machine a user can learn all required processes and steps to operate it. However, shifting a very expensive machine from the production process to the training process can be cost inefficient for the industry. The production must be halted to perform training exercises. This solution is very good only in case of machine not used at a defined period of time. The simulation by a computer is efficient for "work from home", although a user is missing the practical experience of using and maintaining a CNC machine. What is learnt is only software.

The usage of the CNC device simulator is good for basic learning when starting training of a CNC operator. A user can learn how to load and run programs; however, training of the usage of a physical machine is also missing and a device simulator is needed. The VR solution comes with many pros. It can be used at any place without special high-cost devices, a user can learn all required process of CNC operation, all based on programmed training, and what an employer needs from a potential employee. Although the contact is simulated, the nowadays VR solutions, including the headsets and controllers, can bring reliable experience for everyone.

With all this, it should be emphasized that the VR environment can guarantee the automation of personnel preparation processes for the industry while maintaining the reproducibility and accuracy of procedures. Critical is the fact of obtaining a high satisfaction rate of survey participants with regard to VR technology.

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