Journal of Manufacturing Processes 96 (2023) 176–192

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Investigating the differences in human behavior between conventional machining and CNC machining for future workforce development: A case study

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ARTICLE INFO

Keywords:
Conventional machining
CNC machining
Workforce development
Operating behavior
Cutting strategy

ABSTRACT

Due to the high efficiency and consistent product quality, CNC machining has gained a dominant role in the modern machining industry. However, conventional machining still has its significance for certain production settings, e.g. prototyping, and machining workforce preparation. CNC and conventional machining require particular skills and knowledge, which can be unique to specific types of machine tools or overlap to a certain extent. With increasing production volume demands and an aging workforce, a need for efficient quantification, preservation and transfer of said skillsets arises to ensure effective preparation of future professionals and the undisrupted operation of the manufacturing industry. Moreover, the observed shift towards human-centered manufacturing systems in the Industry 4.0 necessitates obtaining an in-depth understanding of human roles in machining. The following paper proposes a novel research approach based on collection and analysis of eye-tracking and video data supplemented by verbal interviews, surveys and self-assessment. A conducted case study spans the entirety of the machining process, from part evaluation, cutting strategy determination, machining operations, to process re-evaluation and optimization. The results show that far greater variability in cutting strategy in terms of operation order, number of operations and used production tooling between consecutive production runs can be observed for conventional machining, with little variation in those terms noted for CNC-based production. Overall, the collected data has allowed to gain an insight into the machinist's decision-making processes and the rationale for observed cutting strategy changes, allowing for potential future application of the proposed research method in improving the machining training and potentially aiding process design by applying the outcomes of studies performed with the use of presented research method to expert systems and future CAM/CAE software solutions.

1. Introduction

The machining industry is a vital section of economies around the world, with substantial employment figures – in the USA alone, the industry employs over 300,000 machinists [1]. Computer Numerical Control (CNC) plays a dominant role in today's machining industry, as computers and CNC machine tools are nearly ubiquitous in machine shops and design offices worldwide. The advent of CNC and Computer Aided Design/Manufacturing (CAD/CAM) has allowed to take productivity, part quality and complexity to new heights, rendering the conventional machine tools comparably inefficient and obsolete to an extent, especially in large-scale production and manufacturing of complex parts [2]. Despite this, conventional machine tools are still employed both in production and educational/training settings. Both CNC and conventional machine tools require certain skills and expertise to operate, which can either overlap in certain areas or be exclusive to the particular type of the machine tool or the production process. The issue of an aging machinist population in the USA is reported by industry sources, with the average age of trained professionals in the field reported as either 45 years [3] or as high as 56 years [4] for highly skilled machine tool operators. As the workforce is shrinking while the industry is experiencing substantial growth, a dire need for efficient, robust methods of quantifying, preserving and transferring machining knowledge becomes evident to ensure uninterrupted training of new professionals and applications in expert systems for process design. To achieve this goal, the focus of research work in the field needs to be

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https://doi.org/10.1016/j.jmapro.2023.04.037
Received 19 November 2022; Received in revised form 8 April 2023; Accepted 12 April 2023
Available online 2 May 2023

shifted from machine tools and novel machining processes to the workforce and human aspects of the industry, as even the most sophisticated machine tools still require skilled professionals to be operated in a safe, efficient and profitable way [5]. Failing to recognize the gravity of the impact of the aging machinist workforce and insufficient interest in machining jobs in younger populations is expected to have a severely adverse effect on productivity and competitiveness within the industry [6].

The advent of Industry 4.0 brought about a heavy focus on the machine-centered approach to the design of manufacturing processes and a push for total process automation and human replacement. However, one of the underlying assumptions of this approach is the presence of a "magic human", a being that does not exhibit variations in performance and does not commit fatal errors in their interaction with the automated system. Rephrasing that statement essentially means that the systems were designed with the machines as their centerpiece and an underlying assumption of the human conforming to them, instead of being human-centered. This shortfall was identified in open literature [7], with innovative approaches to workplace improvement surfacing subsequently. Examples of new solutions include adaptive human-centered workspaces that conform to the worker's individual characteristics and preferences to ensure maximized productivity and ergonomics [8,9], process gamification to enhance the human experience in production environments [10,11] and the use of cobots (cooperative robots) assisting the workers in their tasks [12] instead of total automation and replacement of human workforce. Development of an AR-assisted conventional machine tool training system, was showcased in [13], motivated by an existence of a knowledge gap, as many of the previous works focused solely on training systems for CNC machine tools. The authors have suggested that the vocational education on conventional machine tools is vital, as they require more expertise and skill to operate. The importance of human factors in Industry 4.0 was emphasized in [14], where the authors have made a claim that many human-centric aspects in the industry were ignored to date, such as the assessment of perceptual and cognitive demands of humans. Thus, the authors of that study have identified certain crucial human factors, such as psychosocial needs of humans within Industry 4.0 systems and the need to account for perceptual, cognitive and motor capabilities of workers in system designs, emphasizing that they should be integrated into future studies concerning Industry 4.0.

There are several examples of work in open literature concerning the broad field of machinist knowledge and expertise. Sivalogathan et al. [12] have conducted a machining sector analysis regarding the machinist capability and skillset and their dependence on the type of machining (conventional vs. CNC). In the course of their study, the authors have found that while CNC machines and the expertise required to operate them are vital in the modern manufacturing industry, a strong expertise in conventional machining translates to a higher operator skill level with CNC machine tools. Moreover, while some manual machining capabilities (such as motor skills required to operate the machine controls) are rendered obsolete in the migration to CNC machine tools, many other parts of the machining knowledge can be carried over from conventional processes, benefiting productivity and part quality. Zicklin [15] has investigated the effect of CNC machining on expertise requirements and deskilling of machinists. It was found that conventional and CNC machine tools require varying degrees of proficiency in the following skillsets: motor skills, perpetual skills, abstract planning skills and decision-making skills. An interesting find from this study is the notion that most surveyed machinists found the work on CNC machine tools to be less engaging and providing less job satisfaction, even when they voiced it requires comparable or higher skill levels. Abellan-Nebot [16] has compared the performance of cutting process optimization for a milling process when the procedure is conducted either by a computational algorithm or an experienced machinist. For the optimization goals set in the case study (for example, Material Removal Rate maximization or surface roughness *Ra* minimization), an advanced computational algorithm was shown to perform 6.1 % better than an experienced machine tool operator in terms of meeting the optimization objectives. Opyo [17] undertook a task of developing a knowledge system for determination of part machinability basing partially on machinist expertise, allowing design engineers to design parts basing on pre-sourced machinability information and guidelines, allowing to reduce the number of changes and alterations between the design and manufacturing stages. Se Kim et al. [18] have developed a feature-based method for operation sequence planning, based on decomposition of the part geometry into characteristic features using a graphical approach. In the proposed method, the final selection of the most optimal order of cutting operation sequences is conducted based on machinist expertise, signifying its role in process planning and execution. Chen et al. [19] have devised an AI-based expert system for cutting process planning and optimization based on input from machinist expertise in areas pertaining to general, machine shop and machine level knowledge to help design the best possible process for a given part type, optimization criteria and available equipment. In their machining time estimation method, Takizawa et al. [20] have considered machining expertise and skill level as one of key factors for their predictive model, stressing that accurate machining time estimation for CNC machine tools needs to account for the operator's skill level.

When investigating knowledge, decision making and learning, one needs to clearly define knowledge types and learning outcomes. Review work concerning the assessment of teaching outcomes and knowledge in educational settings [21] proposes a threefold categorization of learning outcomes: cognitive, educational/motivational and skill-based [21–23]. A literature review concerning the broad subject of human-centered manufacturing and human knowledge/expertise reveals recognition of the importance of human factors, knowledge and behavior in production environments. Efficient design of such human-centered industrial environments necessitates collection, quantification and analysis of human knowledge and behavior. Even the most sophisticated high-end systems still need to be designed, overseen and maintained by capable humans possessing appropriate knowledge and skills, with hands-on expertise still being crucial in system design, maintenance and training of workers, if they are to cooperate efficiently and safely in modern production environments. Moreover, as suggested in [13], operation of conventional machine tools yields more effective results in training applications than educational procedures limited merely to teaching CNC tool operation, which shows that the investigation of machinist behavior in the course of conventional machining is a topic worth pursuing for future utilization in training applications.

The work presented in this paper is meant to address the identified knowledge gap concerning lack of in-depth studies of machinist behavior and decision making processes and their influence on select process metrics, such as cutting strategy or part quality outcomes. In the presented work, the authors introduce a novel research method based on collection of gaze tracking and video data for observation of machinist behavior supplemented with surveying, self-evaluation and verbal interview procedures. Expected outcomes include identification of problem/focus areas in part designs and the rationale behind said identification, identification of characteristic behaviors exhibited by machinists during the manufacturing process, an in-depth analysis and quantification of the cutting strategy and obtaining an understanding of how the decision making and cutting strategy changes influence part quality outcomes. Moreover, showcasing how conventional and CNC machining processes differ in terms of process variability and iteration-to-iteration strategy and performance improvements is expected to yield valuable insights in regards to future workforce development applications.

2. Novelty and motivation

While the importance of machinist knowledge and its effect on the process is recognized in open literature, there is a lack of studies that aim to quantify and describe it in the course of an actual machining case study. Therefore, the authors propose a novel approach, devising a comprehensive research method for investigating human knowledge, behavior, decision making and learning processes. The proposed method can be applied to various manufacturing and assembly tasks. In this work, it is applied to machining and demonstrated on the basis of a case study encompassing several complete conventional and CNC machining production runs. The entirety of the manufacturing process, ranging from part design evaluation to process strategy determination and re-evaluation and the machinist's rationale behind their behavior throughout the process are investigated to obtain a fuller understanding of the role of human factors in conventional and CNC machining processes.

Process type (conventional vs. CNC machining) is expected to have a substantial impact on the machinist's decision-making process, the cutting strategy, productivity and part quality. In the course of the production runs, the machinist is anticipated to gradually improve their strategy, using an approach based on their knowledge and learning capabilities to evaluate, correct and optimize the process. The proposed study aims to characterize and quantify this knowledge by using a systematic approach based on verbal interviews, observations of machinist actions, surveying and measurement of process metrics, part quality and analyses of process strategy. This investigation and characterization case study is expected to lead to gathering of fundamental knowledge regarding machinist knowledge, decision making and learning processes. The investigation of gathered data is expected to showcase that certain skills and behaviors related to process improvement and increase in proficiency in machinist expertise are specific to conventional machining, reinforcing the claim that it is still an essential part of training procedures for prospective machinists. Moreover, the proposed method is expected to aid knowledge collection and quantification for use in future workforce development and expert systems for process design.

3. Experimental methodology

To investigate human behavior, learning and decision making in manufacturing operations, a novel research method is proposed in this work. It is a systematic approach utilizing multiple materials and methods, including collection of eye tracking and video data, observation of worker actions, measurement of process metrics, final quality outcomes, knowledge auditing and participant surveying/self-evaluation. The experimental methodology is graphically outlined and showcased using the procedures for a machining process as an example in Fig. 1.

As can be seen in Fig. 1, the proposed method encompasses the entirety of the production process, with key stages differentiated as pre-manufacturing, manufacturing and post-manufacturing. Here, it is noteworthy to stress that the manufacturing stage should be repeated several times per participant, so that they can manufacture/assemble multiple parts. The rationale for this is that letting the human subjects fabricate multiple parts allows to make vital observations concerning their learning and decision making processes.

A detailed description of procedures, methods, equipment and expected outcomes for each stage is given in the following subsections.

3.1. Participants

As the proposed method concerns human behavior in manufacturing operations, recruitment of human subjects is necessary to conduct studies. Depending on the desired outcomes, participants from various populations may be recruited. For example, if one wishes to investigate the effects of professional experience on proficiency/productivity in certain tasks, multiple participants with varying job experience levels can be recruited to perform the same task to obtain outcomes allowing for evaluation of their proficiency at a given task and an analysis of underlying causes and differences in performance.

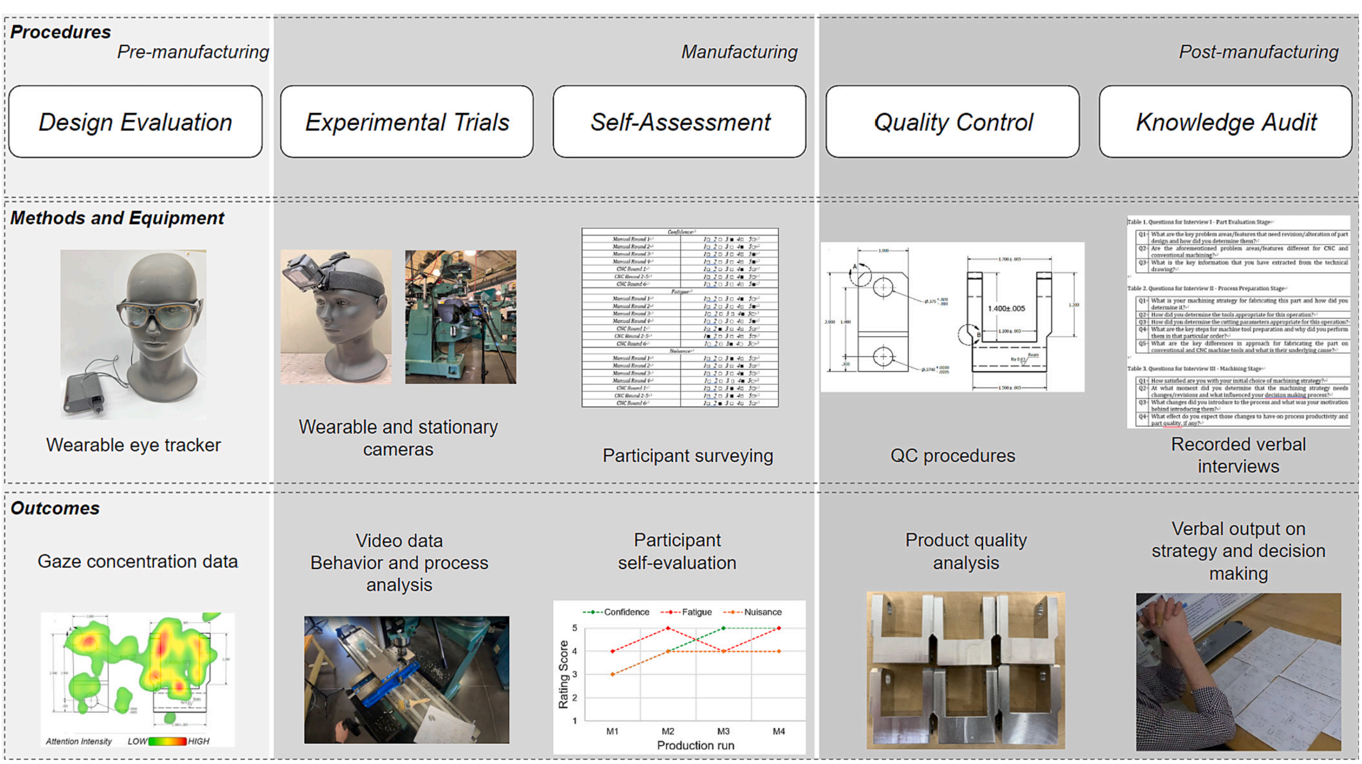


Fig. 1. A flowchart depicting the proposed research procedure.

3.2. Design evaluation (pre-manufacturing)

In the first step, the participants are asked to visually inspect a blueprint / technical drawing of the part / assembly that will be the subject of their work performed during the *Manufacturing* stage of the study. As acquisition of eye tracking data during this stage is proposed, an eye tracking device needs to be employed. Depending on the available equipment and facilities, either a stationary screen-mounted eye tracking device or a wearable eye tracker can be used. Identical lighting and ambient conditions should be provided for all participants to ensure consistency of results. In addition to acquisition of eye tracking data, the participants are encouraged to annotate the blueprints and to verbally express any remarks concerning part design and potential issues that may arise during the manufacturing process. Outcomes from this stage include acquisition of live video, eye movement and gaze fixation data to examine the areas on which the participant concentrates their visual attention when examining a drawing of the component they are tasked with manufacturing. Moreover, collected verbal output and video data from drawing annotation procedures are expected to yield insights into how human subjects use their procedural, situational knowledge and prior experience in design evaluation.

3.3. Cutting trials and self-evaluation (manufacturing)

For this stage of proposed research, three main activities can be differentiated: strategy analysis, behavioral analysis and participant self-evaluation. Video data acquisition is to be conducted during the entirety of this stage to capture the human subject's behavior and work activities. For accurate and robust video data collection, a two-camera setup is proposed. The primary camera is mounted on the subject's head using a harness, capturing the entirety of the production process from the participant's point of view. A secondary camera is mounted on a tripod and remains stationary during the trials. It acquires video from the work zone (defined as the machine/workstation and its immediate surroundings) and serves as a secondary data source in the event of primary camera failure. It also serves as a source of video data from a second perspective, which may prove useful when certain portions of the video feed from participant perspective are obstructed by objects used during the production process and/or the human subject's hands. Stills from example video footage captured with the use of the proposed setup during a milling process are shown in Fig. 2.

3.3.1. Strategy analysis

To perform a strategy analysis, acquired video data can subsequently be used to evaluate the manufacturing strategy employed by the human subject(s). A graphical approach is proposed here, similar to process planning sheets employed in industrial practice. Here, let us consider two distinct examples. For assembly processes, a series of sketches depicting individual assembly operations in the order of progression can be prepared to investigate how the workers approach the assigned tasks and whether there is variability between consecutive trials. For machining, a series of sketches depicting individual operations can be prepared, showing them in order of progression to visualize and quantify the used cutting strategies. An example graphical cutting strategy is shown in Fig. 3.

Video data analysis and strategy evaluation are expected to lead to the following outcomes and observations: 1) how the human subjects use their procedural knowledge to solve the assigned manufacturing tasks, 2) how strategic knowledge is used to organize the production process in an efficient, optimal manner as individual trials progress and 3) how the subjects use their situational knowledge to overcome problems and challenges (for example, excessive chip load and/or tool breakage in machining) that arise in the course of production.

3.3.2. Operational behavior analysis

In addition to strategy evaluation, the acquired video data also provides means for behavioral analysis by capturing human behavior during repeat production processes. Characteristic behaviors (examples for machining can include tool setup, cutting, part/stock measurement, interaction with the machine Digital Readout etc.) can be identified, classified and their percentage contribution to total fabrication time can be calculated subsequently. Examples of possible outcomes include investigating how motor-based skills of the subjects improve between trials by 1) evaluating the total production time per part, using a Total Part Yield (TPY) metric to calculate the number of parts produced per hour and 2) quantifying the change in proficiency with which the equipment is operated by calculating the contribution of interaction with machine controls (such as table cranks, spindle controls, Digital Readout etc.) to the total cutting time.

3.3.3. Self-evaluation

Between consecutive manufacturing trials, participant self-evaluation procedures are planned. This will provide the human subject(s) with an opportunity to subjectively quantify their performance

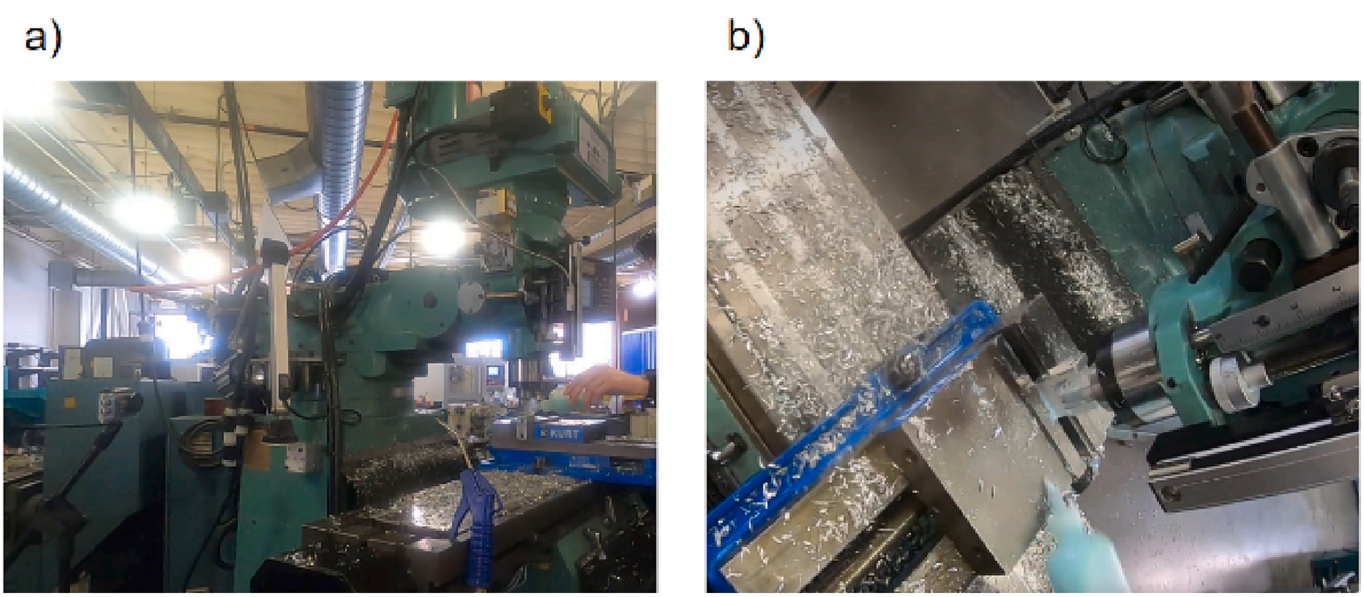


Fig. 2. Example stills showcasing video data acquisition outcomes from machining trials from a) the work zone and b) from the machinist's point of view.

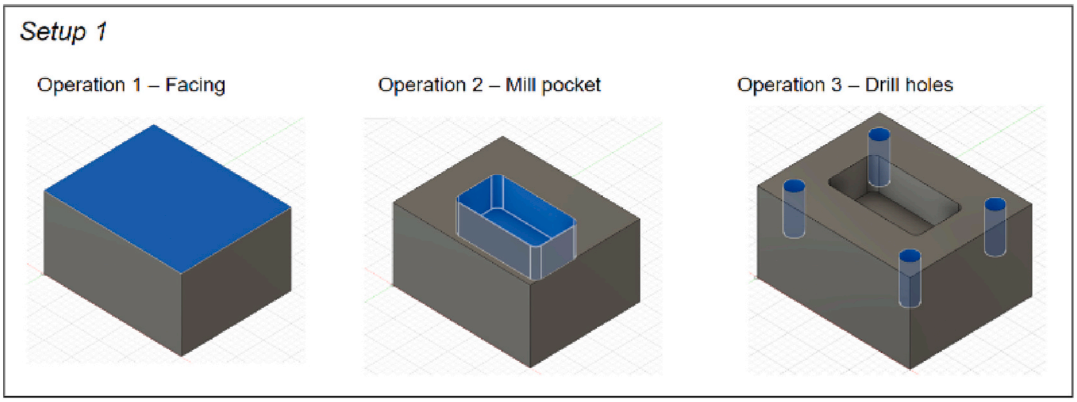


Fig. 3. A graphical illustration of the cutting strategy, showing the progress of milling and drilling operations in machining.

based on personal feelings and perception of the activities performed during this stage. This self-rating approach is based on a standardized scale and three human-centered metrics, as outlined below:

1) Confidence: Rate on a scale of 1–5 how confident you were with your decision making and expected outcomes for this production trial, where 1 is no confidence and 5 is absolute confidence.
2) Fatigue: Rate your perceived physical fatigue and stress/overload during the production trial on a scale of 1–5, where 1 is no fatigue/discomfort and 5 is severe fatigue/discomfort.
3) Nuisance: Rate on a scale of 1–5 the nuisance aspect during the cutting trial – that is, how burdensome/inconveniencing it was to perform the tasks, where 1 is no inconvenience/nuisance and 5 is severe inconvenience/nuisance caused by the task.

Conducting the participant evaluation procedures allows for collection of data regarding self-perceived confidence and skill levels. Comparison of this subjective self-assessment with measurable outcomes, such as total manufacturing/assembly time or finished component quality will allow to investigate whether a link exists between them. Hence, it can provide a way of connecting the self-assessed proficiency, confidence and motivation to measurable metrics, facilitating their evaluation in an objective manner.

Overall, for the *Manufacturing* stage procedures for the proposed research method, it is to be noted that the investigators are not to interfere with any part of the manufacturing process outside of performing the self-evaluation procedures with the human subject(s) between individual trials. They are to retain full control of their manufacturing strategy and are free to use any tools, equipment etc. at their own discretion, without receiving any outside help, guidance or suggestions from the investigators or other workers and staff.

3.4. Quality control (post-manufacturing)

After completion of the manufacturing trials, the fabricated parts are to undergo quality control (QC) procedures. Evaluation of product/assembly quality should be done by means of comparing the end product with technical specifications laid out in blueprints, technical drawings and product specification sheets. The main outcome from performed quality control procedures is quantitative assessment of the effect of strategy revisions and changes in participant behavior on end product quality.

3.5. Knowledge audit (post-manufacturing)

After completion of manufacturing trials, a comprehensive verbal interview is to be conducted with each human subject to collect their verbal output concerning the process they were tasked with performing. The two main purposes of this knowledge audit are: 1) to obtain additional understanding of how the participants used their prior knowledge in process preparation and execution and 2) to investigate their decision making and learning. Hence, the interview questions are divided into three distinct sections. Section 1 concerns the pre-manufacturing stage of design evaluation. Section 2 addresses production activities other than manufacturing proper, such as process planning, choice of equipment, tools, machines etc. Section 3 contains a set of questions pertaining to the manufacturing process itself. Example questions for the proposed knowledge audit are shown in Table 1.

The proposed knowledge audit is to serve as a source of supplementary information, as the analysis of previously discussed eye tracking and video data might not always provide decisive information concerning human knowledge, learning and decision making. Hence, additional verbal output from the human subject might be needed to understand *how* they apply their knowledge to the process, learn and alter their approach to problems and *why* they perform certain actions.

4. Case study

To showcase the proposed research method, as a machining case study, a single participant was tasked with fabricating a batch of identical parts on conventional and CNC machine tools. As per, Fig. 4 the

Table 1
Post-manufacturing knowledge audit questions.

	Stage 1 – Part Evaluation
Q1.1	What were the key problem areas/features that seemed problematic and needed revision/alteration and how did you determine them?
Q1.2	What was the key information that you have extracted from the technical documentation?
	Stage 2 – Process Preparation
Q2.1	What was your strategy for fabricating this part and how did you determine it?
Q2.2	How did you determine the tools, equipment and machinery appropriate for this production process?
Q2.3	How did you determine the parameters and procedures appropriate for this production process?
Q2.4	What are the key steps for machine, equipment and workplace preparation and why did you perform them in that particular order?
	Stage 3 – Manufacturing
Q3.1	How satisfied were you with your initial choice of manufacturing strategy?
Q3.2	At what moment did you determine that your initial strategy needs changes/revisions and what influenced your decision-making process?
Q3.3	What changes did you introduce to the process and what was your motivation behind introducing them?
Q3.4	What effect did you expect those changes to have on process productivity and part quality, if any?

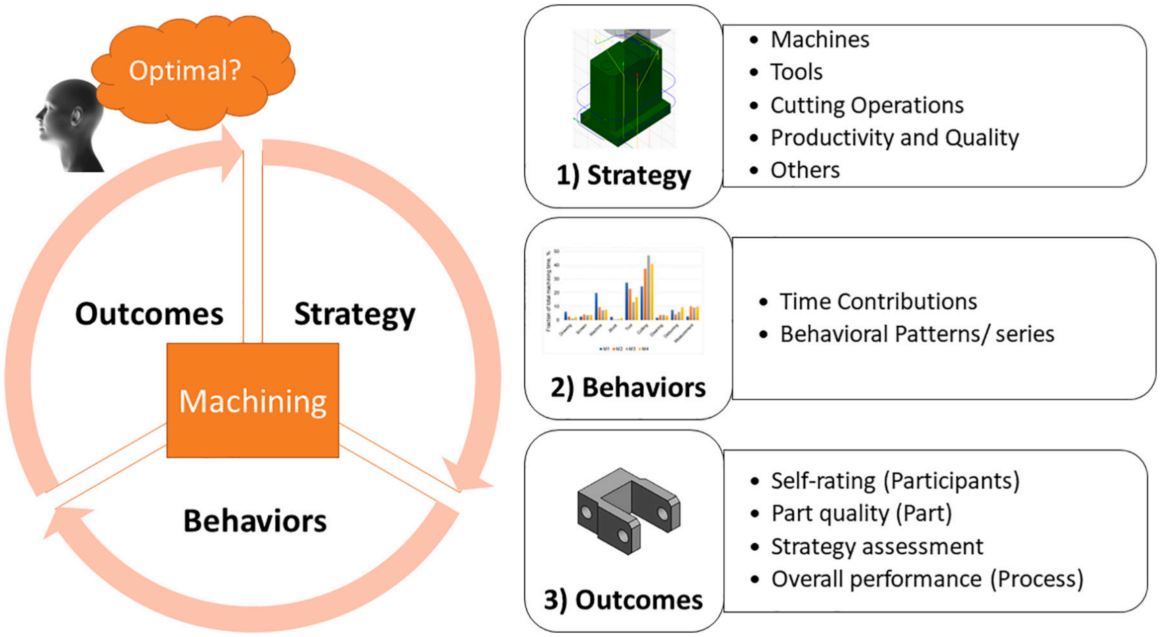


Fig. 4. Application of the proposed research method to a machining case study.

main expected results from the performed machining case study are classified into three distinct categories: strategy results, behavioral results and general outcomes. These factors form the entirety of the outcomes related to the machining process and have a strong relation to each other. Strategy assessment concerns the choice of machine tools appropriate for fabrication of a given part, tools and fixtures, cutting operations and their order, changes in productivity and product quality related to variations in cutting strategy between process iterations. Behavioral results include identification of specific behaviors related to machining activities and calculation of their contribution to total cutting time in each process iteration. General outcomes include self-rating scores, post-manufacturing part quality control results, cutting strategy evaluation and an overall assessment of machinist performance.

4.1. Participant and equipment

The participant was a 24-year-old male recruited from the Rochester Institute of Technology student population, with 3 years of machining experience. Prior to participating in this study, the participant had completed formal training concerning CAD/CAM software use and both conventional and CNC machining operations using the same machine tools as employed in this study. The participant voluntarily provided all the above information and was informed what data will be collected in the course of the study and gave informed consent before the start of the study.

The cutting trials were conducted on manual conventional and CNC milling machines. A TRAK K3 FMX conventional vertical mill was used for the manual production. An OKUMA GENOS M460-VE vertical machining center was used in CNC production processes. All of the performed production runs were recorded in their entirety, with video data acquisition accomplished by means of using a two-camera setup. One stationary GoPro camera mounted on a tripod was used to capture the footage from the cutting zone (machine tool and its immediate surroundings). A second head-mounted GoPro camera was employed to capture the process from the participant's point of view.

4.2. Design (hardcopy drawing) evaluation

Prior to production, the participant was tasked with examining the drawing of a leaf spring shackle part (Appendix 1) and evaluating its design for machinability before manufacturing it. The participant wore a Tobii Pro 3 wearable eye-tracking device during their visual examination of the drawing, which allowed for acquisition of eye movement and gaze fixation data to examine the areas on which the participant concentrated their visual attention. The design evaluation procedure was performed in a laboratory setting. Lack of external distractions was ensured. An artificial light source was placed directly over the whiteboard containing the hardcopy of the technical drawing to ensure appropriate lighting conditions. The original and revised drawings are presented in Fig. 5, along with a heatmap generated from collected eye tracking data, representing the participant's gaze concentration.

The results from visual examination and evaluation of the part design show that the participant's attention has concentrated predominantly on the pocket feature of the shackle part (see Fig. 5 c)). The gaze concentration is in line with subsequent concerns expressed by the participant and revisions to the drawing implemented after part evaluation was concluded. After visual examination of the drawing, the participant had verbally expressed their concerns regarding the depth of the pocket feature and had inquired whether it can be reduced by 0.1 in. As this alteration allows the part to retain its functionality, it was implemented in the drawing revision. This constituted the only alteration to the part design and the participant has not expressed any other major concerns related to part design. Regarding the rationale behind the introduced design alteration, the participant has expressed 1) structural integrity concerns (*"the width of the wall between the pocket and the side of the shackle at its bottom would be insufficient"*) and 2) machinability concerns (*"this feature will be difficult to machine to this depth with the available equipment"*) in the post-examination interview. The concerns expressed by the participant did not pertain specifically to conventional or CNC machining, but rather addressed the machinability of the part in a holistic manner, regardless of process type.

The outcomes of the drawing evaluation procedure show that the gaze concentration of the participant is in line with the areas and features that lead to voicing of concerns with the part's design in terms of machinability and structural rigidity. However, as these results constitute an outcome for a single participant, it cannot be decisively stated that the gaze concentration will always be inextricably tied with features of the drawing that lead to raising concerns regarding machinability. This matter, along with the matter whether particular workpiece features will lead to universally expressed machinability concerns warrants

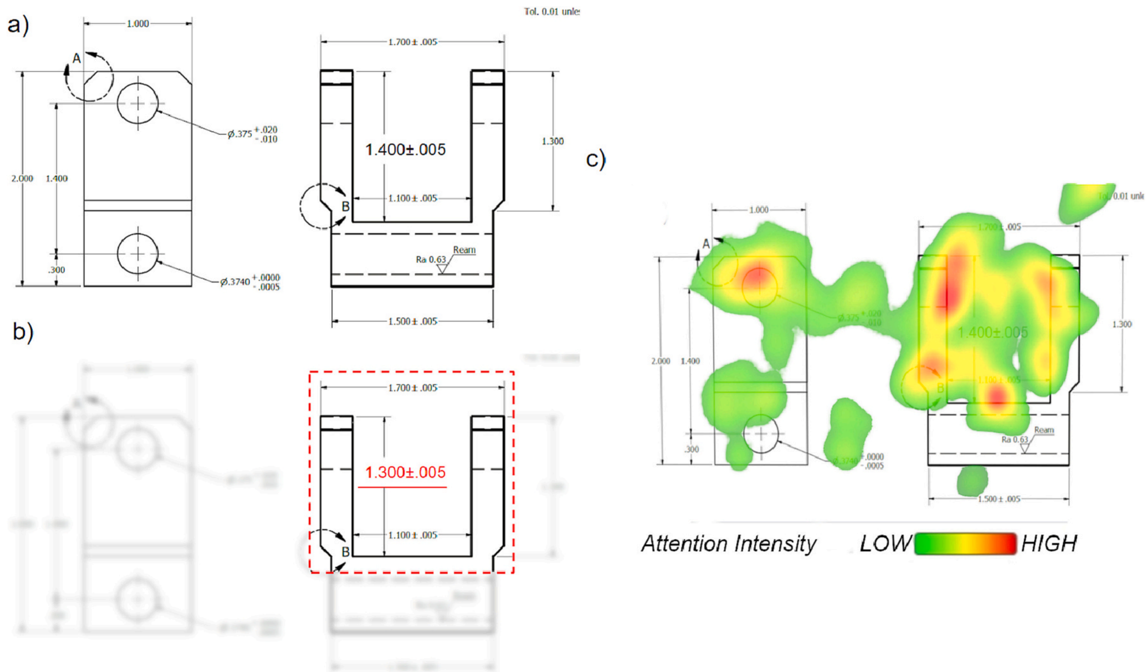


Fig. 5. a) Original part drawing, b) revised part drawing with altered features highlighted, and c) heatmap representing the participant's gaze concentration during the design examination procedure.

further investigation in a study involving multiple participants.

4.3. Machining strategy analysis

4.3.1. Conventional machining

The conventional machining strategy for performing production runs was identified from captured video data and evaluated separately in a graphical flowchart depicting the order of operations with end part geometry after each operation. Workholding changes are noted on the flowchart, with the view of the workpiece depicted relative to the XYZ Global Coordinate System (GCS). For all operations, the stock was mounted in a 2-jaw milling vise and parallels, unless noted otherwise. Manually machined parts are labeled in chronological order. For presented machining strategy flowcharts, only altered operations are depicted graphically, and unchanged operations are carried over with proper text annotation.

A graphical depiction of the machining strategy for the first conventional milling production run is shown in Fig. 6, and this part was used as a point of reference to analyze the variations in machining strategy in subsequent production runs. As shown in Fig. 6, the machining strategy for the first part, M1, consists of a total of 12 operations performed in 8 setups. The part was not reoriented in the workholding for Operations 1–5, from which point onwards every subsequent Operation was associated with a setup change. For Operations 10–12, a

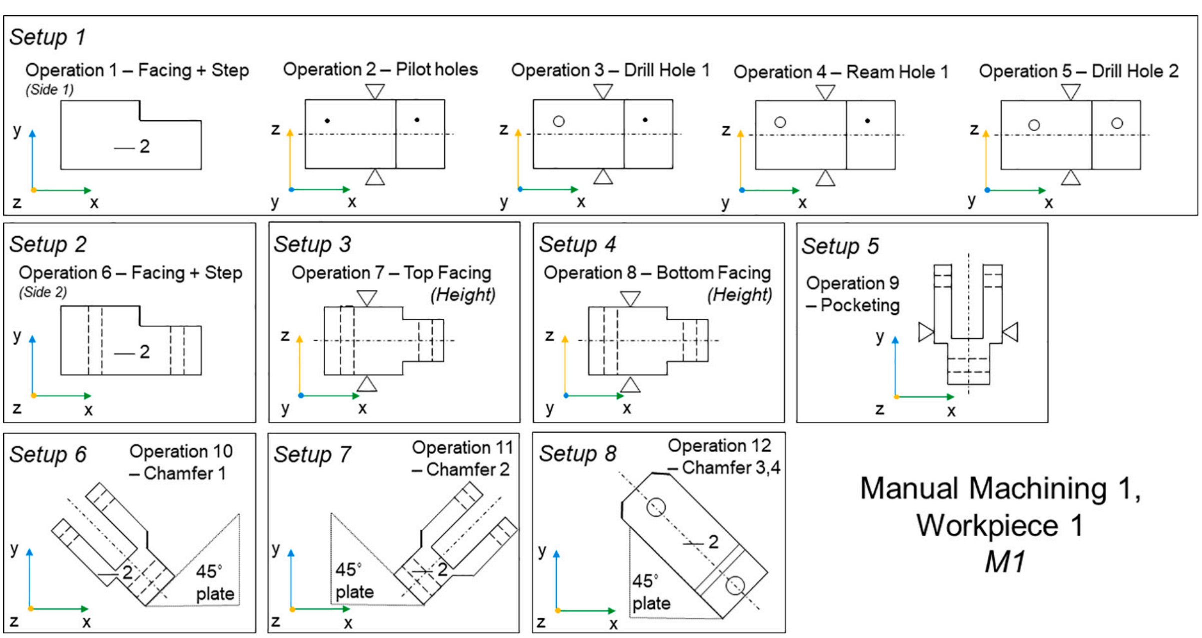


Fig. 6. Visualization of the machining strategy employed for the first manual production run M1.

45° angle plate was used to set the workpiece at a reference angle to manufacture chamfer features on the part.

After the first production run, the participant was allowed to freely introduce changes to their machining strategy, as graphically presented in Fig. 7. All the operations carried over from the first production run are not graphically depicted and are annotated as (M1). As seen in Fig. 7, the total number of setups has decreased by one, while the number of operations has increased by one. The participant added Operation 12 (M2) – Face to Height, as the lack of this Operation was an omission on their part for Workpiece M1, resulting in one of the part dimensions not meeting quality standards. The participant simplified the process by merging Operations 3 & 5 (M1) into Operation 4 (M2), drilling both holes without tool change. Operations 10 & 11 (M1) were eliminated from the process and replaced with chamfering performed immediately after side facing, introducing Operations 2 & 7 (M1), eliminating the need for two separate setups and the use of a 45° angle plate. Chamfering the top surfaces of the shackle was also performed differently, without the use of an angle plate – an end mill was used and small values of XY stepover were used by the participant to machine the chamfer feature (Fig. 7, Operation 13 M2).

As previously, the participant was allowed to change their cutting strategy for manufacturing in the M3 production run, with the new strategy graphically presented in Fig. 8. As previously, all the operations carried over from the first and second production runs are not graphically depicted and are annotated as (M1) or (M2). Examination of the third iteration of the part cutting strategy depicted in Fig. 8 reveals that the number of setups has remained unchanged, whilst total operation count has increased by 1. The only major change introduced to the process is division of the pocketing operation into two new operations, marked as Operation 11 and 12. For the third production run, the participant has fabricated a keyhole feature immediately after facing the part to height, without a fixturing change. Subsequently, they have machined out the remainder of the pocket in a manner similar to the procedure employed for parts M1 and M2. After completing part M3, the participant has expressed that he would like to conduct another production run, as they felt there is still room for process improvement. Therefore, they were allowed to machine part M4 after evaluating and altering their strategy, which is depicted graphically in Fig. 9.

As per Fig. 9, the total number of setups has remained unchanged relative to parts M2 and M3, while the total operation count has been reduced by 4 in comparison with part M3. The first major change is Operation 1 (Fig. 9) where the part has been faced to width on one side, and relief/chamfer features were fabricated on both sides in Operation 4, 5 (Fig. 9). Subsequently, Operations 9 & 10 (M3, Fig. 8) were merged into a single operation (Operation 6, Fig. 9) in which the part was faced to height in one setup. The reaming process for Hole 1 was conducted manually on a drill press at the end of part manufacturing – this marks a change from parts M1-M3, where the reaming was done on a milling machine immediately after hole drilling.

After manufacturing the part M4, the participant was asked if they feel there is any room for process improvement and whether they would introduce any subsequent changes to the cutting strategy when manufacturing part M5. The participant answered no to those questions - hence, the conventional machining trials stopped after fabricating part M4.

As the operation count varies between strategies used to fabricate parts M1-M4, ratio of changed operations R_c (Eq. (1)) was used as a measure of cutting strategy variability.

$$R_c = \frac{n_C}{n_T} \bullet 100\% \quad (1)$$

where R_c is the ratio of changed operations, %; n_C is the number of new operations in a given production run not carried over from previous iterations of the process and n_T is the total number of operations per given production run. The results of R_c calculations rounded to the nearest integer for parts M2-M4 are grouped in Table 2.

Results from Table 2 clearly indicate that most variability was observed for parts M2 and M4. A number of substantial changes to the cutting strategy was introduced between parts M1 and M2, including the elimination of angle plate fixturing for chamfering operations, conducting hole drilling in a single operation and introducing an additional facing operation to ensure the part meets prerequisite dimensional tolerance standards. As expressed by the participant in a post-manufacturing interview (see Section 4.5 for reference), changes between M1 and M2 were motivated mostly by insufficient part quality after the first production run. Moreover, the participant tried to increase process transparency and productivity – hence the elimination of special fixturing and merging of operations where possible. There is little variability in the cutting strategy for parts M2 and M3, where the only distinction is the separation of the pocket machining into two separate

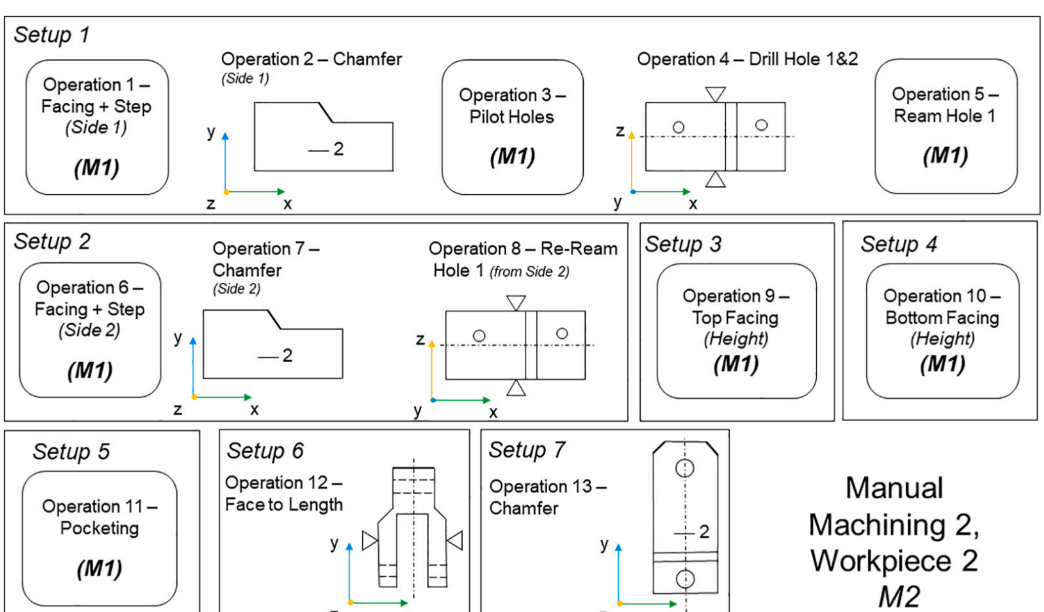


Fig. 7. A graphical representation of the machining strategy for Workpiece M2.

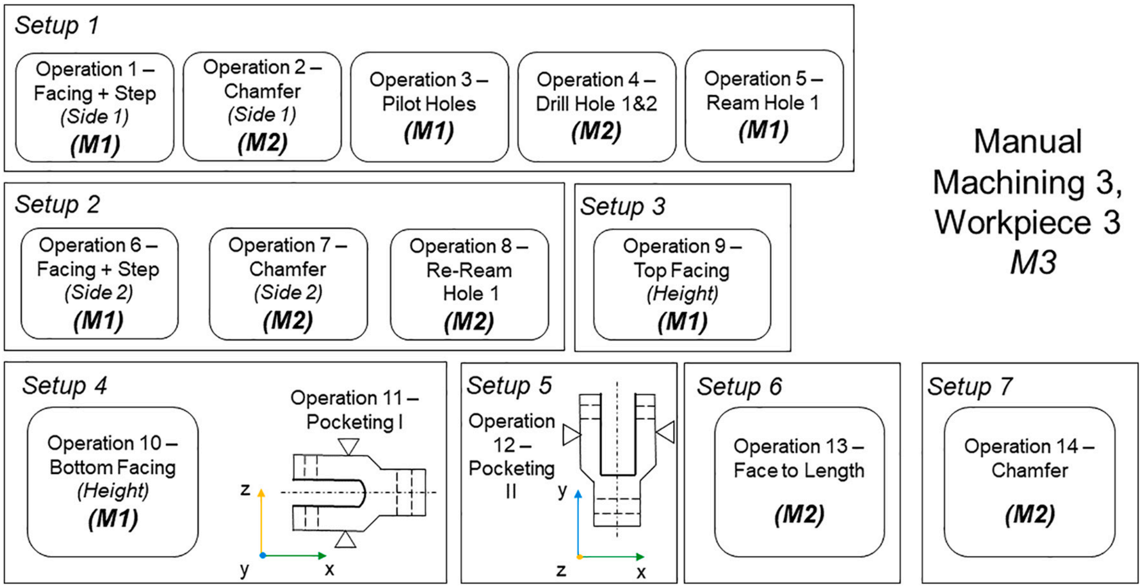


Fig. 8. Cutting strategy employed to fabricate Workpiece M3. Cutting strategy employed to fabricate Workpiece M3.

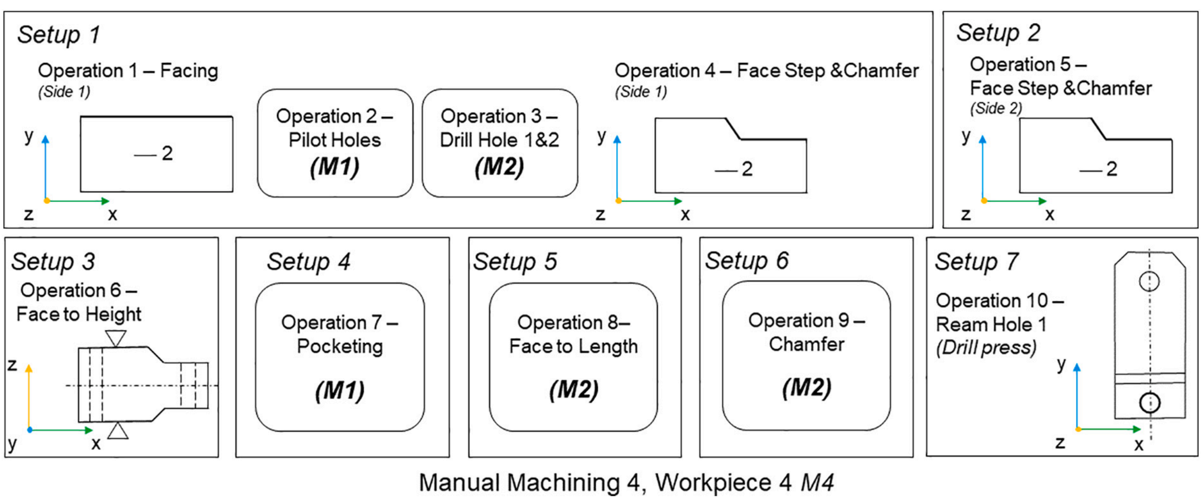


Fig. 9. Machining strategy for part M4.

Table 2
Ratio of changed operations between process iterations, conventional machining.

Part code	M2	M3	M4
R_c, %	46 %	14 %	50 %

operations. The remainder of the process has been left intact by the participant. The highest R_c value was noted for part M4, where the participant has merged/eliminated certain operations – namely, facing to width and height from both sides has been eliminated and replaced by single facing Operations 1 and 6 (Fig. 9), respectively. The reaming operation (Operation 10, Fig. 9) has been moved to the end of the process and conducted on a separate machine tool – namely the drill press. The main motivation behind the introduction of those changes, as voiced by the participant in the interview, was the aim of increasing process productivity by reducing the number of setups and operations.

4.3.2. CNC machining

The evaluation of the CNC machining strategy was conducted in a manner similar to the one analysis presented in Section 4.1. A series of screen grabs from the CAM software shows the progression of machining operations and the corresponding CNC toolpaths. CNC machined parts are labeled NC1-NC4 in chronological order. For schematics concerning parts NC2-NC4, only altered operations are depicted graphically, with operations carried over from previous versions of the process described with an appropriate annotation. The machining strategy employed for the NC1 production run is shown graphically in Fig. 10.

As seen in Fig. 10, the CNC machining process for the shackle part consists of a total of 12 operations performed in three setups. After the initial production run, the participant was allowed to evaluate the process and introduce changes to the CNC toolpath. The revised version of the cutting strategy employed to manufacture the part NC2 is shown in Fig. 11.

Fig. 11 shows the cutting strategy used by the participant to manufacture the part NC2. Calculation of the R_c metric reveals that 27 % of the operations were altered in comparison to the NC1 production run. The alterations have concerned an addition of deburring cycles (Operations 8, 12 and 15, Fig. 11) and a finish pocketing cycle (Operation 14, Fig. 11). The rest of the process has remained unaltered. After part NC2

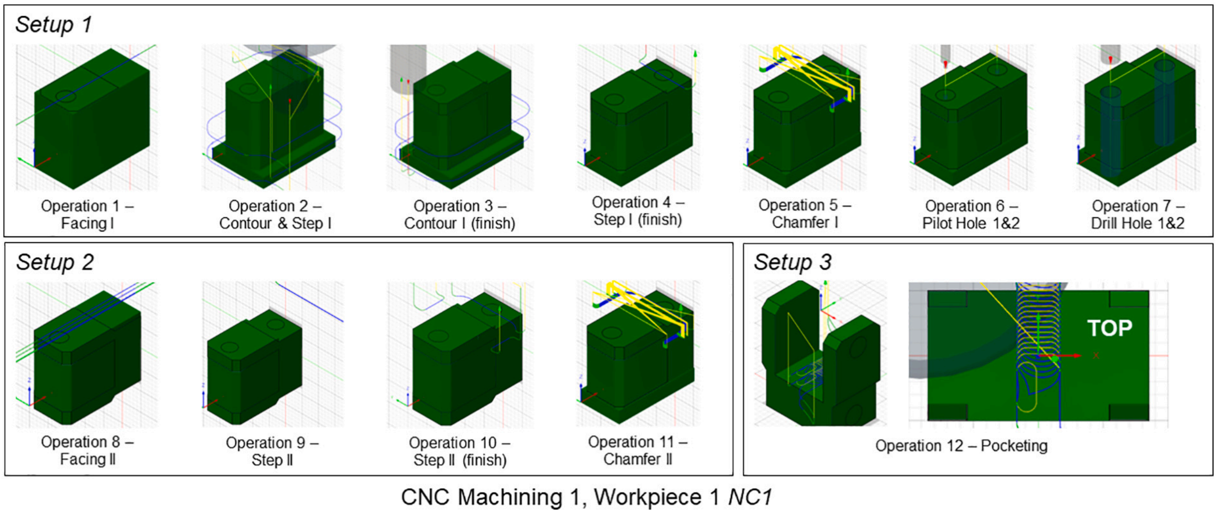


Fig. 10. CNC machining strategy employed by Participant 1 to manufacture part NC1.

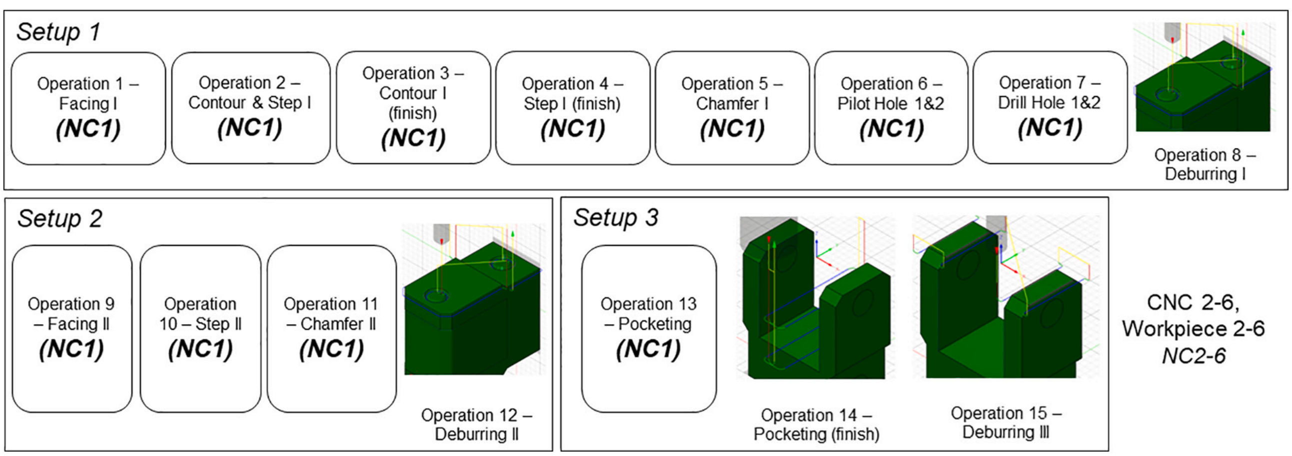


Fig. 11. CNC machining strategy utilized to manufacture part NC2 and subsequent parts NC3–4.

was completed, the participant was given the opportunity to reevaluate the cutting process and introduce changes to their cutting strategy to machine the next part. Despite the opportunity, the participant has not voiced any concerns with the NC2 cutting strategy and has chosen to employ it to fabricate parts NC3–4 as well. The only changes concerned adjustments of cutting parameters for chamfering and pocketing operations – feedrate v_f was altered. As the study concerns the cutting strategy in regard to operations, setups and toolpaths, the cutting parameter changes were not analyzed here. The rationale behind cutting parameter alterations was given by the participant in a subsequent post-process interview (see Section 4.5) – the participant has used their auditory perception of the process to decide on cutting parameter changes where they felt that the chip load was not optimal. This observation is in line with a previous study [24] which has shown that trained machinists make use of their auditory perception for process evaluation and fault detection. Overall, it can be clearly seen that the cutting strategy for the presented case study has exhibited far less variation – in conventional machining, changes were introduced between each iteration of the process and R_c values ranged between 14 and 50 % (see Table 2), whereas for CNC machining, the cutting strategy was altered only between parts NC1 and NC2, with alterations concerning only the addition of deburring cycles and a finish pocketing operation.

After production of part NC4 concluded, the participant was asked if they feel there is any room for process improvement and whether they would introduce any changes to the cutting strategy or CNC toolpaths if production was to continue. The participant gave a negative answer to those questions - therefore, the CNC production stopped after fabricating the part NC4.

4.4. Operational behavior analysis

4.4.1. Conventional machining

To further investigate the conventional machining behavior from captured video data, particular participant's machining-related activities/operations were identified and categorized into 9 distinct categories: drawing evaluation, screen examination, machine interaction, stock evaluation, tool preparation, cutting, cleaning, deburring, and measurement. Behavior categories with corresponding characteristic operations are shown in Table 3.

Percent contributions of characteristic operations to overall cutting time for each conventional production run (M1 - M4) are shown in Fig. 12. To facilitate comparison and evaluation, cutting time for each production run was normalized to allow for comparison of percentage contributions of characteristic operations to the total cutting time. Based on results shown in Fig. 12, the four dominant behavior categories are as follows: #3 (Machine), #5 (Tool), #6 (Cutting), and #9 (Measurement).

The key findings stemming from the behavior observations for manual production runs are as follows:

Table 3
Classification of characteristic operations for conventional machining.

Label #	Category	Operations
1	Drawing	• Reading the hard copy of the drawing • Calculation of cutting parameter values by using a smartphone or a calculator • Putting remarks/annotating the drawing
2	Screen	• Examination of the machine tool Digital Read Out (DRO)
3	Machine	• Adjustment of the spindle/table position by using handles and cranks before or after the cutting
4	Stock	• Annotation of the stock/workpiece • Visual examination of the stock/workpiece
5	Tool	• Preparation of cutting tools • Changing the tools and fixtures
6	Cutting	• Using the machine tool for cutting/drilling
7	Cleaning	• Cleaning the working zone and/or the workpiece
8	Deburring	• Performing deburring operations
9	Measurement	• Inspection of cutter dimensions • Inspection of stock/workpiece dimensions

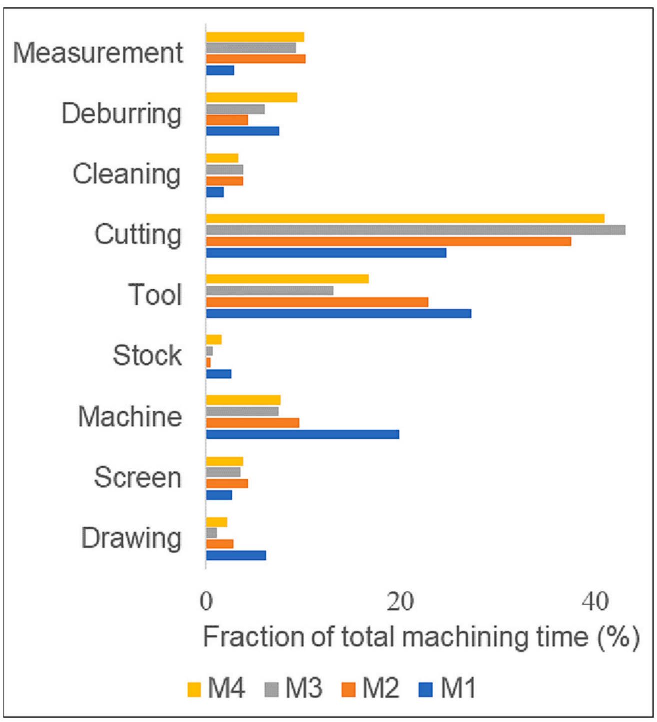


Fig. 12. Percentage time contribution of characteristic behavior categories for conventional machining.

- #3 (Machine): The participant spent the largest percent of time on handle manipulation in the course of the M1 production run. Time devoted to behavior #3 was reduced significantly in M2 and subsequently decreased in the following production runs. As the participant gradually became more acquainted with the specific machine tool and the fabrication process for the part of interest, the time spent on machine tool operation became smaller for each subsequent production run.
- #5 (Tool): Tool preparation time was steady between runs M1 and M2 and has declined approximately by 50 % for the M3, M4 production runs. Note that this operation includes the time spent by the participant on looking for and assembling the necessary cutters, production tooling/fixtures and coolant, which might be located in different sections of the machine workshop. This behavior constituted a majority of time assigned to this category, while the time allocated for changing cutters between operations was comparably insignificant in any of the production runs. Observed trends for tool preparation time are similar to machine interaction (#3) – when the participant becomes more familiar with the process, time allocated for behavior #5 is reduced.
- #6 (Cutting): The cutting took the shortest time for the M1 production run, increasing for runs M2 and M3 before experiencing a decrease for the ultimate production run M4. There is an observable link between cutting time and quality concerns noted between runs M1 and M2. After the first production run, the conducted measurements have revealed unsatisfactory quality. Hence, the participant has changed their strategy and placed greater emphasis on quality control and meeting dimensional tolerances, which caused an increase in cutting time.
- #9 (Measurement): In M1, participant 1 did not devote a significant amount of time to measurement activities. In all subsequent production runs starting from M2, the workpieces were measured frequently between cutting operations. As part quality issues were found after run M1 was finished, measurements became a greater area of focus between runs M2 to M4, and the operator devoted more attention and time to them.

In terms of percent contribution of characteristic operations to total cutting time, two major changes can be noted for M2 and M4 production runs, respectively. For M2, the concern of quality improvement has led to increased cutting (+87 % relative to M1) and measurement (+330 % relative to M1) times. Small savings in cutting time (−28 % relative to M3) were noted for M4, where the approach was more time-savings oriented, as the participant has gained increased confidence in the assumed strategy and partially shifted their focus towards time savings. Behaviors #6 (Cutting) and #9 (Measurement) have significantly changed when different cutting strategies were adopted between production runs, whereas the impact of cutting strategy variation is not particularly obvious for behaviors #3 (Machine) and # 5 (Tool). The strategy changes were minor in run M3; however, the machine interaction time had gradually declined. Similarly, tool preparation time declined by 50 % in respect to the previous production run.

4.4.2. *CNC machining*

A similar video data analysis was applied to study the CNC machining, and the participant's operational behavior was defined using slightly different characteristic categories and corresponding activities related to them, as outlined in Table 4 and Fig. 13, respectively.

After analyzing the Performed CNC production runs, it was found there are three dominant operator behavior categories, namely: #2

Table 4
Classification of characteristic behaviors for CNC machining.

Label	Category	Operations
1	Drawing	• Reading the hard copy of the drawing • Calculation of cutting parameter values by using a smartphone or a calculator • Putting remarks/annotating the drawing
2	Screen	• Examination of and interaction with the machine tool DRO
3	Controller	• Adjustment of spindle/table position by using a handheld controller (jogging)
4	Stock	• Annotation of the stock/workpiece • Visual examination of the stock/workpiece
5	Tool	• Preparation of cutting tools • Changing the tools and fixtures
6	Cutting	• Using the machine tool for cutting/drilling • Using a conventional drill press for reaming
7	Programming	• Examination of and interaction with a PC computer, CAD/CAM software
8	Deburring	• Performing deburring operations
9	Measurement	• Inspection of cutter dimensions • Inspection of stock/workpiece dimensions

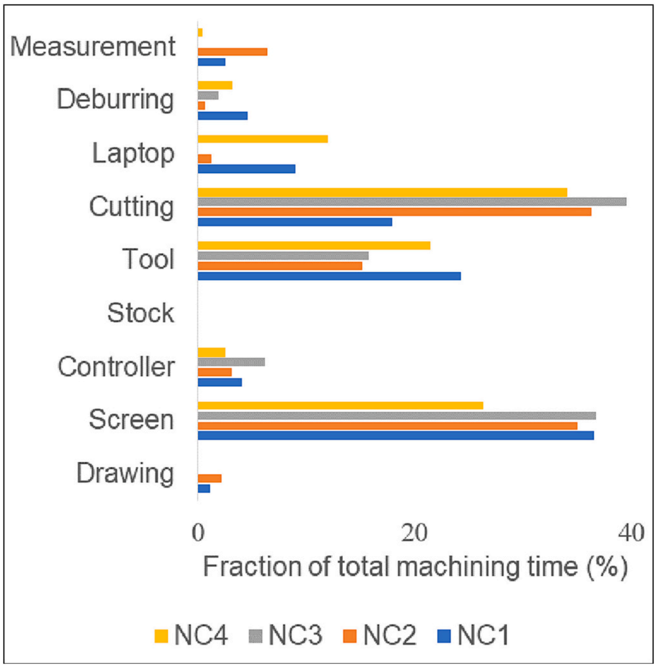


Fig. 13. Percentage time contribution of characteristic behavior categories for CNC machining.

(Screen), #5 (Tool), and #6 (Cutting). A Graphical representation of percentage time contributions to overall cutting time is shown in Fig. 13. The key findings are listed below:

- #2 (Screen): The participant spent the longest time in NC1 interacting with the controller screen panel. The interaction time has dropped slightly in NC2, again reaching the level observed for the first run on the NC3 production run, and then decreasing by approximately 10 % for the final NC4 production pass. This hints towards the observation that the participant has become more acquainted with the process on the final production run and could devote less time to interacting with the machine tool DRO.
- #5 (Tool): The longest tool preparation time was noted for NC1. Afterwards, the tool preparation time declined and has reached a steady level for NC2 to NC4 runs. A similar observation to the one made for behavior #2 can be made here - as the participant becomes more accustomed to the production process, their time spent on tool preparation declines.
- #6 (Cutting): Longer cutting times were noted for production runs NC2 and NC3, with the percent contribution of this category to total machining time dropping again for the final production run - however, the observed cutting time is still substantially larger than for the first performed production run (approximately 18 % vs. 35 % for NC1 and NC4, respectively). The cutting time increase was tied to the cutting parameter changes made by the participant - the post-process interview outcomes (Section 4.5) have revealed the rationale behind those changes after production was concluded.

There are certain differences and similarities in behavior category contributions to total cutting time when production runs were performed on conventional and CNC machine tools. It is easily observed that two behavior categories are dominant regardless of process type - #5 (Tool) and #6 (Cutting). While peak total contributions of those categories for process type vary (~28 % vs. ~25 % for Tool between conventional and CNC production, respectively and ~ 47 % vs. ~39 % for Cutting between conventional and CNC, respectively), they still dominate the percentage time contribution to total cutting time. The most observable difference is a substantial variation in category #2 (Screen), where it can take up as much as approximately 38 % of total manufacturing time in CNC machining, whilst the highest value noted for conventional production was around 5 %. This is inherent to the type of the process - in conventional machining, DRO observation is used only to set the tool offset and observe the XYZ tool coordinates during machining. Meanwhile, CNC machining necessitates constant interaction with the DRO for inputting the NC program, starting/stopping the machine tool, monitoring the process and making changes to it. It is also noteworthy that substantially more time was devoted to category #9 (Measurement) in conventional machining, where the operator had more control over the process (as cutting motions are performed by the operator himself, rather than the NC controller) but also had substantially more room for error - hence, it can be inferred that more time devoted to measurement is tied to the need for constant validation of performed operations and checking for their adherence with quality requirements stated on the technical drawing. The last claim is substantiated by the observation that category #1 representing the drawing examination time exhibits higher peak values for conventional vs. CNC manufacturing (~7 % vs. ~3 %, respectively).

4.5. Quality assessment

After fabrication of all parts via manual and CNC machining has concluded, individual part quality was evaluated separately for manual and CNC machining.

The procedure consisted of performing five repeat measurements of each characteristic part dimension, as specified in Fig. 14. Averaged measurement results were used in subsequent quality control procedures.

The first step concerned the holistic part quality assessment, where each actual part dimension was compared with nominal dimensions from Fig. 14. Each actual dimension was assigned a score q_s of 0 if it did not fall within tolerance bounds and a score of 1 if it met the specification. This has allowed for the calculation of part quality Q_p per Eq. (2).

$$Q_p = \frac{\sum_{i=1}^{n} q_s}{n} \bullet 100\% \tag{2}$$

where Q_p is part quality, %; q_s is dimension quality score (0,1) and n is the number of characteristic dimensions. Quality control results for all fabricated parts are shown in Fig. 15.

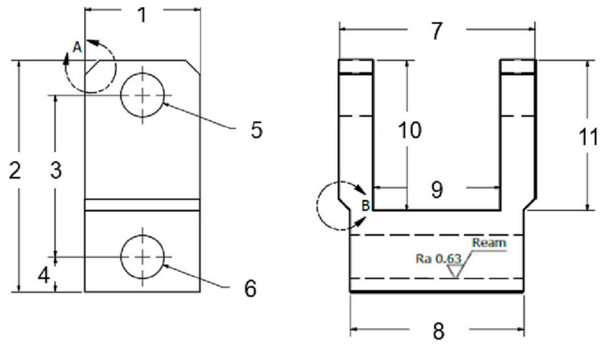
As seen in Fig. 15, there is a considerable increase in part quality between the first and second production runs in manual machining, after which part quality reaches a stable level for parts M2 and M3, with $Q_p =$ 90 %. The quality drops slightly for the last manual production run by approximately 8 %. There is less variability in part quality for CNC machining. Again, the lowest Q_p metric was observed for the first part, with quality reaching a stable level for parts NC2–3. Quality decreases slightly for part NC4.

The second step of the quality control procedure consisted of comparing the individual part dimensions with the nominal dimensions specified on the technical drawing by using a Dimensional Accuracy A_D metric, as specified by Eq. (3).

$$A_{Di} = \frac{D_{Ai}}{D_{Ni}}; i = 1 - 11 \tag{3}$$

where A_{Di} is dimensional accuracy of i-th dimension, –; D_{Ai} is i-th actual (measured) dimension, in and D_{Ni} is i-th nominal dimension, in. The results of D_A calculations for manufactured parts are depicted graphically in Fig. 16, with tolerance limits shown in a red dotted line. A_D coefficient of 1 is equal to 1:1 agreement of measured dimension with its nominal value specified on the technical drawing.

Observation of dimensional accuracy results shown in Fig. 16 confirms observation from holistic part quality assessment – an improvement in part quality is evident especially in the case of manual machining (Fig. 16 a)) where most dimensions for part M1 fall outside of



Dimension	1	2	3	4	5	6	7	8	9	10	11
Nominal Value, (in)	1.000	2.000	1.400	0.300	0.375	0.3740	1.700	1.500	1.100	1.300	1.300
Tolerance, (in)	±0.01				+0.020 -0.010	+0.0000 -0.0005	±0.005			±0.01	

Fig. 14. Characteristic part dimensions evaluated in the quality control stage.

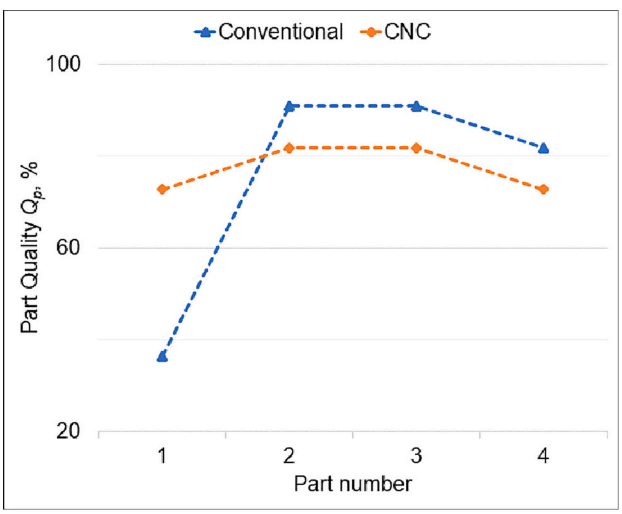


Fig. 15. Quality control results - overall part quality.

the tolerance field and substantial improvement in dimensional accuracy is observed for subsequent parts (M2-M4). For CNC machining (Fig. 16 b)), the difference in part quality between the first production run (NC1) and subsequently machined parts is not as evident as in case of manual production. For all production runs, one can easily see that characteristic dimension 6 (reamed hole for press bushing fitting) is particularly problematic, as the participant was not able to meet the narrow tolerance specifications for this feature, neither in conventional nor CNC production conditions with the use of available shop tooling.

An additional analysis of relationships between participant behavior and performance and end product quality was conducted as a part of the quality evaluation procedure. This relationship was quantified based on investigating the Pearson correlation ρ (Q_P, Y) of collected self-assessment metrics and characteristic behaviors with quality control results, where Q_P is part quality, % and Y are the self-reported nuisance, fatigue and confidence metrics, – or behavior contributions to total processing time, %. The correlation analysis has shown that three factors have a correlation coefficient above $\rho = 0.9$ in case of conventional machining, namely nuisance (self-evaluation), cutting time (behavior), and measurement time (behavior), respectively. This value of the correlation coefficient denotes a strong positive relationship between said metrics/behaviors and part quality. In other words, an increase in the nuisance metric value, cutting time, and measurement time is strongly linked to an improvement in part quality for conventional machining production runs. No statistically significant correlation between self-assessment metrics, characteristic behaviors and end product quality was found for CNC production runs. A summary of correlation results between self-assessment, behaviors and quality control results is presented in Table 5.

4.6. Self-evaluation and interviews

4.6.1. Self-evaluation

The participant was asked to perform a standard-score self-evaluation after each production run was concluded. A graphical representation of self-evaluation results for the confidence, fatigue, and nuisance metrics for conventional and CNC production runs is shown in Figs. 17 and 18, respectively.

Examination of the self-evaluation results depicted in Figs. 17 and 18 leads to the following observations:

- Confidence: The initial participant confidence in the first round of manual machining (M1) was reported as relatively low (3/5) and subsequently grew to 4 in run M2, reaching the highest value of 5/5 during M3 and M4. Interestingly, such an upward trend was not observed in CNC machining. The confidence rating assumed a constant value of 4/5 in all CNC production runs.
- Fatigue: Observation of the average fatigue score allows to clearly infer that the workload and burden are substantially heavier for manual machining, with fatigue ratings alternating between 4/5 and 5/5 values exclusively for manual production runs. For CNC machining, 75 % of the scores are at the lowest fatigue rating of 1/5. A fatigue rating of 2/5 was reported by the participant in the first production run NC1 - this can be attributed to the fact that they were conducting the production of the part of concern for the first time on a CNC machine tool.
- Nuisance: The initial rating for manual machining (M1) is 3/5 and ratings for M2-M4 assume a constant value of 4/5. Analysis of video data shows a high degree of task repetitiveness (even when major strategy alterations are introduced) and a constant demand on the participant to focus on the process (continuous observation of the cutting process, machine tool DRO and re-measurement of the workpiece after most operations). Nuisance scores reported for CNC machining are lower and assume a constant value of 3/5. Analysis of video data shows that the NC production runs are repetitive but require less active attention to the process from the participant, allowing them to remain less focused on constant process

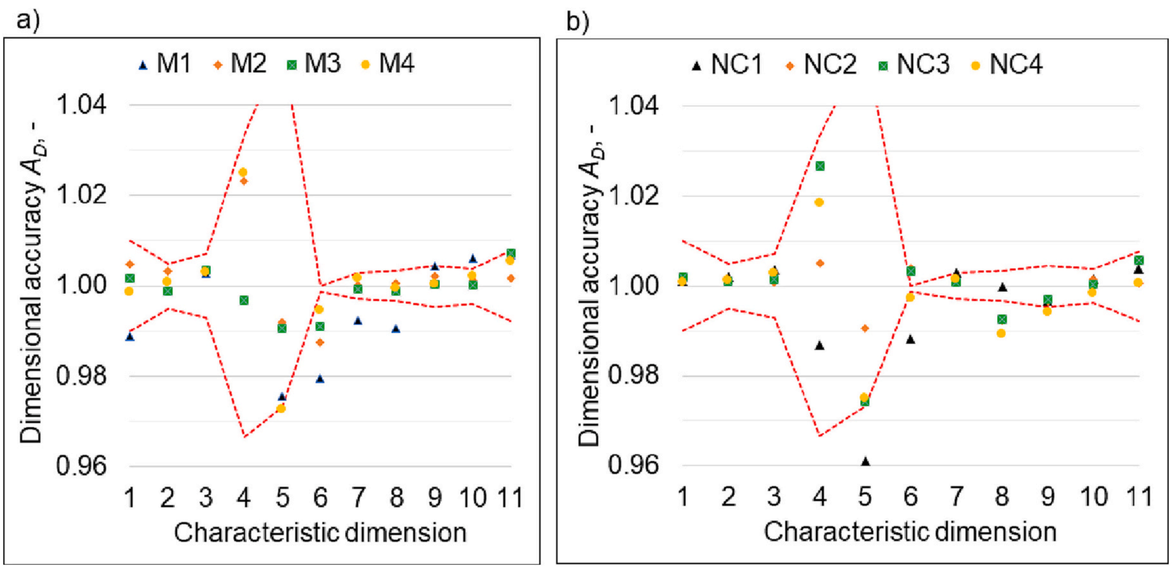


Fig. 16. Dimensional accuracy of characteristic dimensions for parts machined manually a) and on a CNC machine tool b). Tolerance field limits are depicted with a red dotted line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Correlation between self-assessment metrics, characteristic behaviors and part quality. Factors over 0.9 in bold.

		$\rho(Q_P, Y)$ – Manual	$\rho(Q_P, Y)$ – CNC
	Self-Evaluation		
1	Confidence	0.82	0.40
2	Fatigue	0.50	0.29
3	Nuisance	**0.99**	−0.40
	Behavior		
1	Total Time	0.34	0.16
2	Cutting Time	**0.92**	0.65
3	Tool Preparation Time	−0.47	−0.11
4	Measurement Time	**0.95**	0.26
5	Handle and Crank Manipulation Time	−0.88	–
6	Screen manipulation Time	–	0.24

observation and monitoring. This can be seen as the underlying cause for reporting lower nuisance scores.

4.6.2. Post-process interviews

After all manufacturing on conventional and CNC machine tools was concluded, a series of interviews with the participant was conducted. The participant was asked a number of open questions concerning three distinct stages of the production process (recall Table 1).

For the part evaluation stage (QI.1-QI.3) the participant has expressed concerns with two main features of the part – pocket feature depth and chamfers, especially in the context of fabrication on a manual machine, where a less rigid workholding setup is available. It was also brought up that access to a 5-axis CNC machine tool would have facilitated part fabrication – this was a recurring theme in the course of the interview. Key information extracted from the drawing in the course of its examination included bulk part dimensions (length, width) that allowed to determine appropriate stock dimensions. Referencing of dimensions on the technical drawing influenced the machinist's decision-making process in regards to the order of operations.

Key information inferred from the process preparation stage (QII.1-QII.5) pertains to the cutting strategy choice and differences/similarities in process planning for conventional and CNC production runs. The participant's general strategy concerned fabrication of larger features followed by secondary features, such as chamfers and holes. Different

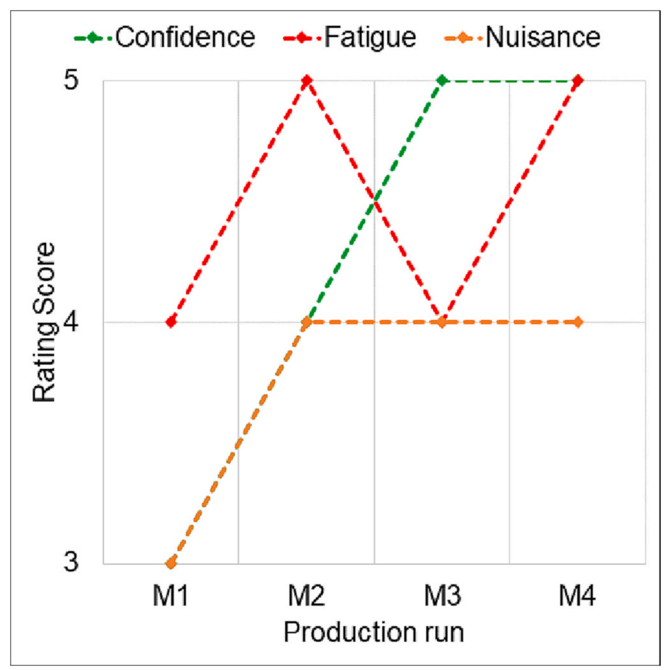


Fig. 17. Self-rating values for manual production runs.

tools were chosen for conventional and CNC production, based on machine tool capabilities. Interestingly, the participant relied primarily on the information from a smartphone application and the CAM program for appropriate choice of parameters and subsequently corrected them on the basis of their auditory perception of the process. Major differences observed in terms of the number of setups and nature of machining operations in conventional and CNC production runs were revealed to have roots in machine tool capabilities – for example, the participant expressed that they have more flexibility for the number of operations per single setup when conducting the process via means of CNC machining. Certain operations were performed manually or on a separate machine – such as reaming on a drill press – either due to time saving or accuracy concerns.

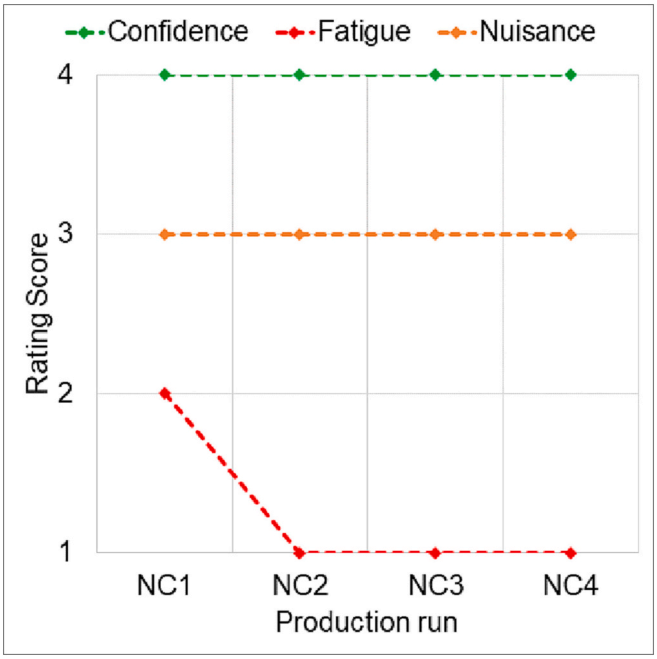


Fig. 18. Self-rating values for CNC production runs.

For the machining stage (QIII.1-QIII.4), the participant has expressed general satisfaction (75 % self-rated satisfaction) with their initial choice of assumed cutting strategy – while they felt there was room for improvement in terms of certain tooling/setup choices in conventional machining, they expressed little room for improvement in designed CNC production runs – reflecting this, a high degree of satisfaction was expressed when discussing the CNC production strategy. The main motivation for introduction of changes in the cutting strategy was voiced – namely insufficient part tolerance obtained in the first manual production run. After assessing the dimensional accuracy of the part and its visual appearance, the participant introduced changes to the process that they felt would result in improvements of part quality. Parameter values in CNC manufacturing were adjusted based on the auditory perception of the process and problems with workholding. Secondary motivation was reducing the number of setups and simplifying the process where appropriate, without reducing part quality. Recalling the initial assumptions for the study, the participant was instructed to perform at their own pace and no fixed requirements for part fabrication times were set – this is reflected in the post-process interview, where they expressed secondary concern with concentrating on improving fabrication times per production run. This leads to a significant finding – the trained professional focuses more on quality outcomes (dimensional tolerance) and simplifies the process to reduce their own workload, given that part quality is not impacted adversely by said changes. The focus on improving the productivity of the process was greater in the case of CNC production, where little room for improvement in terms of number of setups and operations was available.

5. Conclusions and summary

Basing on analysis and interpretation of the outcomes of this case study, the key findings from performed research work are as follows:

- The case study allowed to understand *how* the machinist applies their knowledge to the process, learns and alters their approach to problems and *why* they perform certain actions. Observed activities and categorized behaviors were successfully tied both to human participant's rationale, as well as measurable process outcomes. Examples include tying the observed reduction in number of operations and changes in used tooling and strategy to the desire of reducing process complexity/machinist workload while retaining part quality, or sacrificing productivity (understood in terms of total machining time) and devoting more time and attention to quality monitoring-related tasks such as measurement or drawing observation to meet specified quality standards when initial quality outcomes were unsatisfactory.
- Substantial variations in cutting strategy and operator behavior were noted for production runs conducted with the use of conventional machine tools, while little variability in terms of cutting strategy were noted for CNC machining. Analysis of the cutting strategy for conventional machining allowed to infer that the process strategy has exhibited noticeably greater complexity in terms of the number of operations and setups. Moreover, cutting strategy between consecutive production runs has exhibited larger variability, with the operator changing the number of operations, used tooling and order of operations. Merging of certain operations to simplify the process was also observed as production runs progressed. For the CNC production, the process has exhibited little variability in terms of the number of operations and no variability in used setups and production tooling. The participant has introduced changes to the cutting parameters based on their auditory perception of the process, a phenomenon which was not observed in conventional machining production runs, where the participant has adopted a more conservative approach and has not voiced any concerns with the used values of cutting parameters in subsequent post-production interviews.
- Conventional production was shown as more appropriate for training in strategy optimization and learning the *do's* and *don'ts* of machining, proving its strong potential for continued use in workforce preparation applications. Collectively, the findings from this case study effectively showcase that the machinists are more engaged in the process when conducting conventional machining for the same part geometry, as they gradually learn the specifics of the assigned production task and learn to improve and optimize it based on both prior expertise and the knowledge acquired in the course of repeated production runs.

In this study, a new research approach for evaluating human performance, learning and decision-making processes in manufacturing operations was proposed. The presented case study was meant to showcase the proposed novel research method proposed by the authors and encompassed the entirety of the production process, starting with part design evaluation, cutting process preparation, machining, part quality control, participant self-assessment and post-process interviews. The study encompassed fabrication of a small batch of parts, spanning a number of production runs performed on conventional and CNC machine tools. Collected data has allowed to capture the changes in the machining strategy and the participant's decision-making process and gain an insight into the rationale and motivations behind observed changes. Moreover, a deeper understanding of how those changes influence select process metrics was acquired using the proposed research method. Observation and analysis of process variability and machinist behavior in the course of conventional and CNC production runs allows to state that conventional machining is more engaging to the operator and leaves wider room for process refinement, presenting more opportunities for learning, acquisition of new knowledge as well as utilization and reinforcement of previously gained expertise.

The performed case study showcases how the proposed method can be used to analyze human behavior, decision-making and various learning outcomes in manufacturing settings. The main limitation of presented work is inherent to its nature – as it is a case study, it cannot be decisively stated that the observed differences between conventional and CNC production, changes in machining strategy, motivations/rationale behind them and their effect on process outcomes are generally applicable to the majority of trained machinists. Therefore, a comparison study is currently being conducted by the authors, where the entirety of the production process will be analyzed in a similar manner when performed by multiple machinists. This study will involve multiple participants from RIT Kate Gleason College of Engineering and deaf/hard of hearing participants from National Technical Institute for the Deaf. The outcomes from this study will not only allow to obtain more insights into the human behavior in machining operations, but are expected to identify key differences between machinist trainees who exhibit no underlying hearing problems and ones that are deaf/hard of hearing. Identification of said differences and observations made with the use of the previously described research method can help adapt the workplaces and workforce development programs to the needs of deaf/hard of hearing individuals, improving student motivation, learning outcomes and job satisfaction.

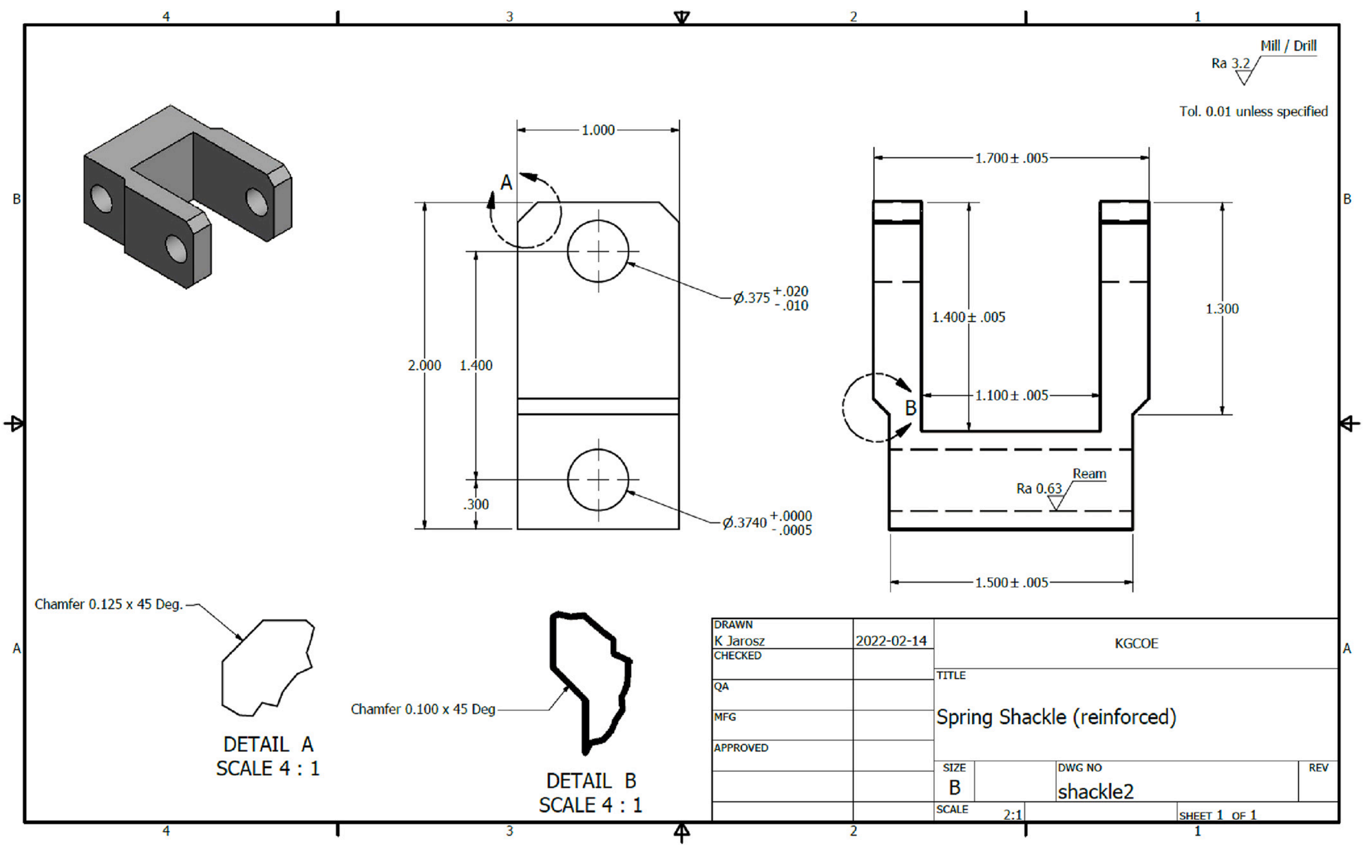
Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rui Liu reports financial support was provided by National Science Foundation. Krzysztof Jarosz reports financial support was provided by Gleason Doctoral Fellowship.

Acknowledgments

The authors gratefully acknowledge the support for this work from the Gleason Doctoral Fellowship program and the National Science Foundation (Award # 2202179).

Appendix 1. Part drawing



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