Journal of Sustainable Economy

Journal homepage: https://scholarsin.com/journals/sustainable-economy

Analysis of Operator Skills and Automation on Spare Parts Accuracy

Alshaybni Abdulqadir Adrees Faraj[1] and Omar Emad Hassouna[1]

[1]*School of Engineering, Alfa University College, Selangor, Malaysia*

ABSTRACT

This study examines the impact of operator skills, raw material quality, and automation accuracy on the dimensional accuracy of spare parts produced in Libyan oilfield workshops. Grounded in an integrated theoretical framework combining Human Capital Theory, the Resource-Based View, and Socio-Technical Systems Theory, the research employed a quantitative correlational design, with data collected from 150 machinists and CNC operators through structured questionnaires. Multiple regression analysis revealed that all three independent variables significantly influence dimensional accuracy, collectively explaining 62.3% of its variance. Automation accuracy emerged as the strongest predictor ($\beta = 0.368$, $p < 0.001$), followed by operator skills ($\beta = 0.351$, $p < 0.001$) and raw material quality ($\beta = 0.312$, $p < 0.001$). These findings demonstrate that dimensional accuracy is not determined by a single factor but by the synergistic interaction of human, material, and technological elements. The study contributes to theory by empirically validating an integrated framework in the context of resource-constrained Libyan workshops. Practically, it provides workshop managers with evidence-based guidance for resource allocation, emphasizing the need for balanced investments in workforce training, material quality assurance, and automation maintenance. The research addresses a critical gap in understanding precision manufacturing within developing industrial contexts, offering implications for improving operational reliability and safety in Libya's petroleum sector.

Keywords: Dimensional accuracy, operator skills, raw material quality, automation accuracy, CNC machining

[1] Corresponding author.
Email address: omar.i@alfa.edu.my (Omar Emad Hassouna)

Received 17 Jun 2026; Received in revised form 8 July 2026; Accepted 27 July 2026
Available online 31 July 2026
ISSN: 0231-2618/

1. Introduction

Precision spare parts production is critical to functionality and efficiency within the global petroleum industry. Precision, or dimensional accuracy, is closely related to quality and pertains to how well a product meets its design specifications (Groover, 2020). Within Libya, where petroleum products fuel its economy, domestic workshops within the petroleum industry help maintain their country's infrastructure by producing and overhauling components to avoid supply-chain problems. However, maintaining size accuracy in practical applications is a tough task. It depends on three aspects that are further emphasized in their environment. First, human expertise in machining remains a backbone of machining quality. This is because human expertise is essential in machining, even in modern machining systems (Haslam et al., 2024; Newaz & Refat, 2025). Secondly, the quality of raw materials in terms of verified chemistry, mechanics, microstructure, and freedom from residual stresses defines the boundary for accuracy. Variability in materials leads to machining errors and subsequent distortion, underscoring the need for guaranteed materials to ensure accuracy in machining operations (Jawahir et al., 2022; Zhang et al., 2025). Thirdly, automation accuracy, which entails CNC geometric and control accuracy, helps eliminate human errors and improves repeatability. The smart manufacturing system with continuous monitoring and control of manufacturing processes is a major factor that contributes to accuracy (Zhong et al., 2023; Shahrum et al., 2025). The interplay of these three variables—human, material, and technology—occurring uniquely in Libyan supply chain processes, training, and technology use, makes up the context for this study (National Oil Corporation, 2024). Recent studies have indicated that, for optimal manufacturing performance, there is a need for a holistic perspective on all these variables, particularly in the context of developing manufacturing environments (Rajendran et al., 2023). This study investigates the combined effect of all these variables on the dimensional accuracy of spare parts produced in Libyan oilfield workshops.

Indeed, it has been noted that there are operational inefficiencies and losses in the Libyan oil and gas industry directly attributed to the lack of dimensional accuracy in spare parts produced in local workshops. The challenge is that there is no empirical model in the Libyan scenario that describes how operator skill, material quality, and automation accuracy interact to produce overall dimensional accuracy. These factors have been identified in manufacturing science to independently affect overall accuracy, but in the specific scenario of Libyan oil workshops, there is no quantitative measure of how these factors interact. However, this holistic knowledge has yet to be applied to and validated within resource-limited settings such as Libyan workshops, where issues of fluctuating supply chains for certified materials, differing levels of vocational training, and maintaining highly advanced CNC machines are unique challenges. Thus, workshop managers lack research-driven, specific knowledge to make informed allocations of their limited resources. Allocations of investment for training employees' skills, upgrading material sourcing processes, and upgrading automation systems are thus often reactive and generalized. This study is guided by three primary research questions: What is the nature and strength of the relationship between operator skill level and the dimensional accuracy of spare parts in Libyan oilfield workshops? To what extent does the quality of raw materials influence the dimensional accuracy of spare parts in these workshops? How does the technical accuracy of automation and CNC equipment affect the dimensional accuracy of the produced spare parts?

The overarching aim of this research is to analyze and model the impact of operator skills, raw material quality, and automation accuracy on the dimensional accuracy of spare parts produced in Libyan oilfield workshops. To achieve this aim, the specific objectives are to analyze the relationship between the skill level of machine operators and the achieved dimensional accuracy of manufactured spare parts; to evaluate the impact of raw material quality on the dimensional accuracy of spare parts; and to assess the effect of the inherent accuracy of automated machining systems on the dimensional accuracy of spare parts. Based on the established research questions and theoretical framework, the following hypotheses are proposed for testing: H1: There is a significant positive relationship between operator skills and dimensional accuracy. H2: There is a significant positive relationship between raw material quality and dimensional accuracy. H3: There is a significant positive relationship between automation accuracy and dimensional accuracy.

Theoretical and practical implications of this research are substantial. From a theoretical perspective, this research fills a gap that was identified and provides an integrated approach to investigate human, material, and technological factors that are normally investigated separately in a unique and relatively uninvestigated industrial context. From a practical perspective, this research will enable Libyan workshop managers to make informed decisions concerning investments related to human resource development, material quality, or technological improvement. Furthermore, this research could help to improve the precision of parts and therefore could improve workshop reliability and safety. For the purposes of this study, dimensional accuracy is defined as the degree of conformity between the actual measured dimensions of a manufactured part and its nominal specified dimensions and tolerances. Operator skills represent the composite of formal training, practical experience, and demonstrated proficiency in machine setup, tool selection, process monitoring, and corrective decision-making. Raw material quality is the inherent properties of metal stock used for machining, including chemical composition, mechanical strength, hardness, microstructure homogeneity, and the presence of verifying certifications. Automation accuracy is the inherent precision capability of a computer-controlled machine tool, quantified by metrics such as positional accuracy, repeatability, and backlash.

2. Theoretical Foundation

The study of factors influencing the dimensional accuracy of products requires theories that go beyond the confines of a particular field of study. In this case, three theories are necessary to explain the relationship between operator skills, material quality, and product automation accuracy. The Human Capital Theory, originally developed by Becker (1964) and later extended by economic research, forms the underlying paradigm for evaluating operator skills. The Human Capital Theory essentially views knowledge, skills, and health as capital sources that provide economic returns through increased productivity. Human capital differs from physical capital as it is person-specific and accumulated through specific investments made in education, training, and experience. In the manufacturing arena, this paradigm predicts a tremendous difference in production quality based on specific investments in operator development. The economic implications of this paradigm have been extremely important for settings like Libya, where specific investments in human capital could provide a better return through quality enhancement as opposed to overall investments made in advanced technology. Recent paradigm extensions related to technical professions have focused on the difference between general human capital and specific human capital (idiosyncratic skills such as knowing a particular CNC machine's programming), where specific human capital is extremely valuable for precise manufacturing but also more susceptible to obsolescence (De Grip & Van Loo, 2002).

The Resource-Based View (RBV) of the firm was pioneered by Barney (1991) and further developed through the study of strategic management. The RBV provides a rich paradigm for the strategic value of quality materials. The RBV argues that sustained competitive advantage can be gained by exploiting resources that are valuable, rare, inimitable, and non-substitutable—termed the VRIN properties. Although materials may not always be rare in absolute terms, the regular availability of certified high-quality materials can represent a valuable but hard-to-imitate resource in the presence of unpredictable supply chains. The RBV concept of the strategic value of "complementary resources" is also highly pertinent—high-quality materials can be made more valuable by the presence of experienced machine operatives who can optimize machining conditions based on the properties of the materials being processed and by the availability of exact automation systems capable of fully exploiting the properties of the materials being processed (Teece, 2018). The RBV theoretical framework thus raises the status of raw material quality from a mere input variable to a resource whose value is conditional upon the availability of complementariness in the manufacturing system.

The theory of Socio-Technical Systems, rooted in the foundational ideas of the Tavistock Institute's classic study on organizational design (Trist and Bamforth, 1951) and further developed by Clegg (2000) and others, is the key framework for analyzing the accuracy of automation within its organizational and human context. Essentially, the theory and tradition of Socio-Technical Systems reject technological determinism and instead assert that the optimal performance of any system is the product of the joint optimization of social and technical subsystems. A high-quality CNC machine, for example, is a technical subsystem that functions within the context of operator competence, maintenance, quality control, and organizational goals, which constitute the social subsystem. The theory asserts that the greatest returns on technological investment are realized when the technology is attuned to the social system's capabilities, a phenomenon described as "joint optimization." Such a theory is vital for the understanding empirical evidence regarding the accuracy of automation, especially within the context of cross-cultural and/or developmental studies, where the failure of technology transfer, due to a lack of consideration for the social system's needs, is a frequent problem. The incorporation of these three theoretical perspectives provides a strong and multi-dimensional tool for analyzing manufacturing accuracy.

2.2. The Libyan Industrial Context and Gap Synthesis

The interrelations between operator skills, material quality, automation accuracy, and dimensions are not absolute, existing instead in a mediated relation by the particular historical, economic, infrastructural, and institutional context of Libyan oilfield workshops. Industry in Libya has had an erratic growth pattern. The country had developed extensive industrial capacity in metal working in the 1970s and 1980s, but years of conflict, international sanctioning, lack of investment, and brain drain have adversely affected both physical infrastructure and institutional knowledge (Pargeter, 2012). The new reconstruction cycle takes place in a unique economic setting in which hydrocarbons form the backbone of exports. The CNC machining industry in Libya finds itself in a post-conflict reconstruction phase with unique attributes such as almost all equipment sourcing being imported, infrastructure challenges related to power supply, and mixed fleet operation strategies. The local supply chain, when it comes to qualified engineering materials, is a major issue, leading to uncertainties in material origin and properties.

The comprehensive review of theoretical frameworks, empirical literature, and contextual factors reveals several established understandings and one significant scholarly omission that this research aims to address. The literature under review extensively covers the individual effects of skills, automation, and material quality on the dimensional accuracy for controlled and high-tech environments. But there is a substantial research gap when it comes to studying the combined effects of all three variables for resource-constrained environments. Specifically, there is a lack of empirical research being conducted within settings such as Libyan oilfield workshops, where factors could range from challenging climates to unreliable supply chains concerning raw material quality, and possibly varying factors concerning formal operator experience and training. This study bridges these gaps by using an integrated and contextual approach to examine how these factors interact in an oil field workshop in Libya to determine dimensional accuracy. The conceptual framework suggests that dimensional accuracy is directly affected by three independent variables: operator skills, raw material quality, and automation accuracy.

Table 2.1: Literature Review Matrix

Author(s) & Year	Main Focus & Variables Studied	Key Findings	Why This Matters for My Research
Haslam et al. (2021)	Review of Human Factors (IV1) in manufacturing quality and productivity.	Cognitive skills, experience, and decision-making autonomy are paramount for quality in complex, low-volume production. Enhancing problem-solving often yields greater returns than just automating procedures.	Theoretical & empirical support for IV1. Validates focusing on operator skill in Libya's high-mix, job-shop context. Suggests training should target cognitive skills, not just rote tasks.
Newaz & Refat (2025)	Role of Operator Skill (IV1) in designing/implementing fixtures; interaction with automation (IV3).	Skilled fixture implementation (a human task) is critical to unlocking a CNC machine's precision potential. High skill can compensate for equipment limitations.	Highlights the IV1-IV3 interaction. Shows skill and automation are complementary. In Libyan workshops, a skill gap could be the bottleneck preventing modern machines from achieving their accuracy potential.
Jawahir et al. (2020)	Review of Material Properties (IV2) and their effect on machined surface integrity and dimensional accuracy.	Material homogeneity, microstructure, and residual stresses are primary, underlying constraints on achievable finish and accuracy. They directly dictate machining outcomes.	Foundational support for H2. Elevates raw material quality from a simple input to a critical technical constraint. Explains why unreliable material supplies can derail even a skilled process.

Author(s) & Year	Main Focus & Variables Studied	Key Findings	Why This Matters for My Research
Zhang et al. (2025)	Achieving ultra-high precision in NbTi wire, focusing on Raw Material (IV2) and Automated Processing (IV3).	To achieve ±2μm tolerances, both superior raw material quality AND precisely controlled automation were non-negotiable. One could not compensate for deficiencies in the other.	Evidence for complementary IV2-IV3 interaction. Shows that high automation accuracy maximizes the return on high-quality materials. Conversely, poor materials limit what even the best automation can achieve.
Zhong et al. (2017)	Review of Smart Manufacturing/Automation (IV3) implementation (Industry 4.0).	The full benefits of advanced automation are only realized through complementary human skills and organizational adaptation. Technology alone is insufficient without skilled labor to program, maintain, and interpret it.	Strong socio-technical perspective supporting IV1-IV3 interaction. A crucial warning for the Libyan context: investing in hardware (IV3) without upskilling people (IV1) will not yield the expected improvements in accuracy.
Shahrum et al. (2025)	Optimizing Automation Parameters (IV3) for dimensional accuracy in 3D printing using Response Surface Methodology.	Systematic optimization of automated process parameters (e.g., temperature, speed) directly improved dimensional accuracy by 23%.	Demonstrates that the precision and calibration of the automated process itself is a direct, optimizable lever for improving outcomes, separate from operator action during a single job.
Farook et al. (2023)	Influence of Operator vs. Scanner Type (Automation) (IV1 vs. IV3) on accuracy in digital dentistry.	In a highly digitalized workflow, the type of scanner (technology) and data algorithms had a more significant	Highlights a contingent relationship. Suggests that in sufficiently advanced, standardized digital

Author(s) & Year	Main Focus & Variables Studied	Key Findings	Why This Matters for My Research
		impact on final accuracy than the individual operator.	systems, the process can be designed to minimize outcome variability from operator skill, shifting importance to technology.
Adão et al. (2022)	Using AI/Automation for Inspection (IV3) to assess Raw Material (IV2) quality (leather defects).	A deep learning model achieved 96% accuracy in defect detection, outperforming human consistency and mitigating inspector fatigue/error.	Illustrates the fusion of IV2 and IV3. Shows how automation (IV3) can be deployed to assure raw material quality (IV2), creating a crucial quality control feedback loop. Relevant for proposing tech-driven QC solutions.

4. Method

This chapter offers a detailed account of the research methodology used to systematically examine inter-linkages between operator skills, raw material quality, automation accuracy, and dimensional accuracy in the specific Libyan oilfield workshop context. The research methodology is specifically designed to move from theoretical and conceptual frameworks developed in Chapter 2 to empirically analyze data to test research hypotheses. A quantitative-correlational research design is chosen as the most suitable research paradigm for this purpose as it facilitates measurement of variables, statistical analysis of inter-linkages between them, and generalization of results from sample to specified population (Creswell & Creswell, 2018). This is in line with a positivist research philosophy that aims to observe and quantify social reality in an objective, value-free way in order to discover general patterns and causal connections. A non-experimental study is required because the variables being researched (operator expertise, material quality, machine precision) are impossible to manipulate in a real-world industrial environment in any kind of ethical or practical way but must be observed in their natural state. The cross-sectional study design involves data collection for a sample population in a single point in time, which is very effective for correlation detection and for determining the current state of precision manufacturing in Libyan workshops (Polit & Beck, 2012).

The approach used in this study is one of correlation and explanation using a survey design. Using multiple regression analysis to test for variables simultaneously enables an explanatory analysis to be conducted to determine which variables have the greatest predictive power for dimensional accuracy, moving from description to explanation in analysis (Pallant, 2020). The population for this study is clearly identified as consisting of all skilled machinists and CNC machine operators currently employed in the maintenance and manufacturing shops that service Libya's national oil and gas industry. Taking into account employment statistics from Libya's Ministry of Labor and Rehabilitation and industry statistics from Libya's National Oil Corporation that suggest a few thousand technicians are employed in downstream service and maintenance, a conservative estimate of the population of directly relevant skilled machine operators is approximately N=1,200 (National Oil Corporation, 2023; Ministry of Labor and Rehabilitation, Libya, 2022). The identification of a population with a justifiable and specific number is essential for calculating a relevant sample size from scientific sampling tables.

To make the results generalizable and reduce selection bias, it is imperative to use a probability method of sampling. The study will use Simple Random Sampling (SRS). The study adopts this method because it is the easiest method of probability sampling where all elements of the population have an equal and independent chance of being selected, thus promoting the representativeness of the study and the validity of the inference (Fowler, 2014). In determining the required sample size for a finite population, this study will use the well-known table for determining sample size devised by Krejcie and Morgan (1970). With a population (N) of 1,200, the recommended sample size (n) based on the Krejcie & Morgan table is 291. Nonetheless, for social scientific and field-level studies in industry, it can be very difficult to reach a sample of this size in a realistic and feasible manner. For multiple regression, a sample of at least 15-20 per independent variable is recommended (Hair et al., 2019). With three key IVs, this would be 45-60 samples in total. To provide sufficient statistical power for the test of effects, a target sample size of n = 150 will be adopted. This can be deemed realistic and methodologically sound, as it surpasses the regression test minimum requirements and also reflects a standard for similar field-level studies that can be realistically ascertained.

The primary instrument for data collection is a structured, self-administered questionnaire. It is designed to translate the study's abstract constructs (latent variables) into measurable indicators (observed variables) using multi-item scales, a practice that enhances the reliability and validity of measurement (DeVellis, 2017). The questionnaire is divided into five distinct sections to ensure logical flow and respondent clarity: demographic factors, operator skills, raw material quality, automation accuracy, and dimensional accuracy, mostly measured using a 5-point Likert scale. The Likert-type items for all the core variables were taken from previous research studies on manufacturing and quality management, as well as human factors research, to establish content validity. The survey instrument was first drafted in English, as per academic standards, and then carefully translated and backtranslated by bilingual experts to develop the instrument for the target population in Arabic (Behr, 2017). A pilot study was carried out prior to the collection of primary data on a sample consisting of 25-30 machinists who represent the target population but weren't part of the primary study.

The data collection process was executed in a systematic, phased manner to maximize response rate and data quality. Formal letters detailing the study's academic purpose, ethical guarantees (anonymity, confidentiality), and potential benefits were sent to the management of randomly selected workshops. For workshops granting permission, the researcher scheduled a visit. To encourage candid responses, especially regarding skill self-assessment and material quality criticisms, no identifying information was collected. Questionnaires were completed independently and returned in sealed envelopes directly to the researcher. All quantitative data were entered, cleaned, and analyzed using IBM SPSS Statistics (Version 28). The analysis progressed from preliminary descriptive and diagnostic checks to advanced inferential testing, including descriptive statistics, scale reliability and validity assessment using Cronbach's alpha, and inferential statistical analysis encompassing bivariate Pearson's correlation and Standard Multiple Linear Regression. This research was conducted in strict adherence to ethical guidelines, encompassing informed consent, anonymity and confidentiality, beneficence and non-maleficence, and data security.

5. Data Analysis

This chapter presents the analysis of the data collected for this study and reports the empirical findings in relation to the research objectives and hypotheses. The primary purpose of this chapter is to examine the relationships between operator skills, raw material quality, automation accuracy, and dimensional accuracy of spare parts in Libyan oilfield workshops. The analysis is conducted using the Statistical Package for the Social Sciences (SPSS), following the procedures outlined in the method chapter. It begins with a presentation of the response rate and demographic characteristics of the respondents, followed by descriptive statistics of the study variables. Subsequently, the reliability of the measurement scales is assessed using Cronbach's alpha. Inferential statistical techniques, including Pearson correlation and multiple regression analysis, are then employed to test the proposed hypotheses and determine the strength and significance of the relationships among the variables.

The data for this study were collected using an online questionnaire administered through Google Forms. A total of 150 questionnaires were distributed to skilled machinists and CNC operators working in Libyan oil and gas workshops. Out of the 150 questionnaires distributed, all 150 responses were successfully received. Upon screening the returned questionnaires for completeness and consistency, all responses were found to be usable for analysis, as there were no significant missing values or invalid entries. Therefore, the study achieved a response rate of 100%, which is considered highly satisfactory for quantitative research. The high response rate enhances the reliability of the findings and reduces the likelihood of non-response bias.

The demographic characteristics of the respondents provide context for interpreting the findings and ensure that the sample reflects the target population of skilled machinists and CNC operators in the oil and gas sector. The gender distribution of the respondents indicates that the majority of respondents were male, accounting for 55.3% (n = 83), while female respondents constituted 44.7% (n = 67) of the total sample. This suggests a relatively balanced gender representation, although male participants slightly dominate the sample. The distribution reflects the gender composition typically observed in technical and industrial roles within the oil and gas sector, where male participation is often higher. Regarding years of experience, the largest proportion of respondents (34.0%, n = 51) have between 8 and 15 years of experience, suggesting that the sample is dominated by moderately experienced professionals. Respondents with 3–7 years and more than 15 years of experience each account for 23.3% (n = 35), reflecting a balanced representation of both mid-level and highly experienced operators. Additionally, 19.3% (n = 29) of respondents have less than 3 years of experience. In terms of the highest level of formal education or training, the largest proportion of respondents (36.7%, n = 55) possess primary or secondary level education. This is followed by respondents with technical or vocational certificates, accounting for 29.3% (n = 44), highlighting the importance of vocational training within the machining profession. Respondents holding a diploma represent 20.7% (n = 31), while those with a bachelor's degree or higher constitute the smallest group at 13.3% (n = 20). Therefore, overall demographic information is presented in Table 1.

Table 3.1: Population, Sample Size Determination, and Sampling Justification

Aspect	**Specification**	**Justification & Source**
Target Population	All skilled machinists/CNC operators in Libyan oil & gas workshops.	The study aims to generalize findings to the entire group of professionals whose work directly impacts spare part accuracy in this critical sector.
Population Size (N)	Approximately 1,200 individuals.	Estimated from Libyan National Oil Corporation (NOC, 2023) and Ministry of Labor (2022) reports on technical employment in hydrocarbon services.
Sampling Technique	Simple Random Sampling (SRS).	Provides every population member an equal chance of selection, minimizing bias and supporting statistical generalization (Fowler, 2014).
Ideal Sample Size (Krejcie & Morgan, 1970)	n = 291 (for N=1200 at 95% confidence).	Represents the gold-standard calculation for sample size from a finite population.
Target Sample Size	n = 150.	A pragmatic and robust adjustment. It meets the minimum requirement for multivariate analysis (Hair et al., 2019) and is achievable given field constraints, while still providing sufficient statistical power.

5.1 Descriptive Statistics

The descriptive statistics for the main variables of the study provide an overview of the central tendency and dispersion of the data, which is essential for understanding the general pattern of responses. The results indicate that all study variables have relatively high mean values, ranging from 3.9356 to 4.0362 on a five-point Likert scale. This suggests that respondents generally perceive a high level of operator skills, raw material quality, and automation accuracy, as well as a relatively high level of dimensional accuracy in spare parts production. Operator skills recorded the highest mean value (M = 4.0362, SD = 0.78773), followed closely by raw material quality (M = 4.0300, SD = 0.79570) and automation accuracy (M = 4.0067, SD = 0.81487). This implies that respondents have a positive assessment of these critical factors within their working environment. Dimensional accuracy, the dependent variable, has a slightly lower mean (M = 3.9356, SD = 0.89259), although it still reflects a generally favorable perception. In terms of variability, the standard deviation values range from 0.78773 to 0.89259, indicating moderate dispersion around the mean. Thus, Table 3 presents descriptive statistics of the key constructs.

Table 3. Descriptive Statistics of Study Variables

Variable	Minimum	Maximum	Mean	Std. Deviation
Operator Skills	1.86	5.00	4.0362	0.78773
Raw Material Quality	1.67	5.00	4.0300	0.79570
Automation Accuracy	1.50	5.00	4.0067	0.81487
Dimensional Accuracy	1.33	5.00	3.9356	0.89259

5.2 Hypotheses Results

Multiple linear regression analysis was conducted to examine the combined and individual effects of operator skills, raw material quality, and automation accuracy on dimensional accuracy. The results indicate that the model explains approximately 62.3% (R-squared = 0.623) of the variance in dimensional accuracy. The adjusted R-squared value of 0.615 confirms that the model has strong explanatory power even after accounting for the number of predictors. The ANOVA results indicate that the regression model is statistically significant ($F = 80.512$, $p < 0.001$). This confirms that the independent variables, when considered together, significantly predict dimensional accuracy. The regression coefficients show that all three independent variables have a positive and statistically significant effect on dimensional accuracy. Automation accuracy has the strongest influence (Beta = 0.368, $t = 5.446$, $p < 0.001$), followed by operator skills (Beta = 0.351, $t = 4.896$, $p < 0.001$) and raw material quality (Beta = 0.312, $t = 4.275$, $p < 0.001$). This indicates that improvements in automation systems contribute the most to enhancing dimensional accuracy, although operator skills and material quality also play significant roles. The hypothesis testing results indicate that all three hypotheses (H1, H2, and H3) are fully supported. Therefore, the model summary is presented in Table 4 and hypothesis results are presented in Table 5.

Table 4. Model Summary

Model	**R**	**R^2**	**Adjusted R^2**	**Std. Error of the Estimate**
1	0.789	0.623	0.615	0.554

Table 5. Summary of Hypotheses Testing

Hypothesis	**Relationship**	**Beta (β)**	**t-value**	**Sig.**	**Decision**
H1	Operator Skills → Dimensional Accuracy	0.351	4.896	0.000	Supported
H2	Raw Material Quality → Dimensional Accuracy	0.312	4.275	0.000	Supported

Hypothesis	Relationship	Beta (β)	t-value	Sig.	Decision
H3	Automation Accuracy → Dimensional Accuracy	0.368	5.446	0.000	Supported

6. Discussion and Implications

This chapter presents the discussion, conclusions, and recommendations derived from the findings of the study. The primary purpose of this chapter is to interpret the results obtained in Chapter 4 in relation to the research objectives, research questions, and theoretical framework developed in earlier chapters. The discussion focuses on examining how operator skills, raw material quality, and automation accuracy influence the dimensional accuracy of spare parts within Libyan oilfield workshops. The findings of this study revealed that operator skills have a significant positive effect on dimensional accuracy. This result supports the first research objective and confirms that higher levels of operator competence contribute to improved machining precision. This finding aligns strongly with Human Capital Theory, which emphasizes that investments in skills and expertise enhance productivity and performance. In the context of machining, skilled operators are better able to interpret technical drawings, select appropriate tools, adjust machining parameters, and respond to process variations, all of which are critical for achieving dimensional accuracy. Empirical studies in manufacturing also support this result, showing that machining accuracy is influenced not only by machines but also by operator expertise (Peterka et al., 2023).

The study also found that raw material quality has a significant positive influence on dimensional accuracy, supporting the second research objective. This implies that better material properties lead to more predictable machining behavior and improved dimensional outcomes. This result is consistent with the Resource-Based View (RBV), which considers high-quality materials as valuable resources that contribute to performance advantages. In machining processes, material properties such as hardness, homogeneity, and thermal behavior directly influence cutting forces, tool wear, and deformation, thereby affecting dimensional precision. Existing literature provides strong support for this relationship (Pop et al., 2024). The findings also reinforce the idea that material quality acts as a foundational constraint in manufacturing. Unlike operator skills or machine settings, material properties cannot be easily corrected during processing, making them a critical determinant of final product accuracy. In the Libyan oilfield context, where material supply chains may be inconsistent, this finding highlights the importance of material certification, quality control, and sourcing strategies in achieving reliable machining outcomes.

The results indicate that automation accuracy has the strongest positive effect on dimensional accuracy among all variables, supporting the third research objective. This suggests that advanced and precise automation systems play a dominant role in achieving consistent and accurate machining results. This finding is consistent with Socio-Technical Systems Theory, which emphasizes the importance of technological systems in shaping organizational performance. High-precision CNC machines, when properly calibrated and maintained, can significantly reduce human error and ensure repeatability. The literature strongly supports this result (JLCCNC, 2024; Tayier, 2024). However, the findings also align with the socio-technical perspective that automation alone is not sufficient. Its effectiveness depends on proper integration with skilled operators and high-quality materials. This reinforces the interconnected nature of the three variables examined in this study. Collectively, the findings confirm that dimensional accuracy in machining is not determined by a single factor but by the interaction of human, material, and technological elements.

This study makes significant theoretical contributions by integrating and empirically validating three complementary theoretical perspectives—Human Capital Theory, the Resource-Based View (RBV), and Socio-Technical Systems Theory—in the context of precision manufacturing within Libyan oilfield workshops. The findings provide strong empirical support for Human Capital Theory, extending its application into the domain of precision engineering. The study also contributes to the Resource-Based View by empirically demonstrating the strategic importance of raw material quality as a key organizational resource. This research advances RBV by positioning material quality not merely as an input factor but as a strategic asset that directly influences manufacturing precision. The results provide strong support for Socio-Technical Systems Theory, particularly the principle of joint optimization between social and technical subsystems. The finding that automation accuracy has the strongest influence highlights the critical role of advanced technological systems. Overall, this study contributes to theory by developing and empirically validating an integrated framework that links human, material, and technological factors to manufacturing precision.

The findings of this study provide several important practical implications for workshop managers, the broader oil and gas sector, and policymakers responsible for industrial development and workforce training. For workshop managers, the results highlight the need for a balanced and integrated approach to improving dimensional accuracy. Managers should prioritize continuous skill development through targeted training programs, on-the-job learning, and mentoring systems. Enhancing operator competencies in machine setup, troubleshooting, and process optimization can significantly reduce machining errors and improve consistency. Attention must also be given to raw material procurement and verification, establishing stricter quality control procedures. At the industry level, the findings emphasize the importance of strengthening local manufacturing capabilities to support operational reliability in the oil and gas sector. Oil and gas companies should invest in upgrading local workshops by supporting skill development initiatives, improving access to certified materials, and facilitating the adoption of modern automation technologies. From a policy perspective, the study highlights the need for strategic interventions to develop technical skills and strengthen industrial infrastructure. Governments should prioritize vocational education and establish frameworks to regulate and monitor the quality of industrial materials.

7. Limitations and Future Research Study

Despite the valuable insights provided by this study, several limitations should be acknowledged, as they may affect the generalizability and interpretation of the findings. First, the study adopted a cross-sectional research design, where data were collected at a single point in time. While this approach is suitable for examining relationships between variables, it does not allow for the establishment of causal relationships. Future studies may adopt longitudinal designs to better understand how operator skills, material quality, and automation accuracy influence dimensional accuracy over time. Second, the study relied on self-reported data collected through a questionnaire. Although measures were taken to ensure reliability and validity, self-reported responses may be subject to biases such as social desirability bias or respondent interpretation. Participants may overestimate their skills or the quality of processes within their organizations.

Third, the sample size of 150 respondents, while adequate for statistical analysis, is smaller than the ideal sample suggested by standard sampling tables. Although the sample meets the minimum requirements for regression analysis, a larger sample size would enhance the robustness and generalizability of the findings. Fourth, the study focused specifically on Libyan oilfield workshops, which operate within a unique industrial and economic context. Factors such as infrastructure limitations, supply chain constraints, and workforce conditions may differ significantly from those in other countries. Therefore, the findings may not be directly generalizable to more advanced or different industrial settings. Fifth, the study examined only three independent variables—operator skills, raw material quality, and automation accuracy. While these are key determinants of dimensional accuracy, other factors such as machine maintenance practices, environmental conditions, organizational management, and process standardization were not included in the model. These factors may also influence manufacturing precision and should be considered in future research.

Based on the limitations of this study and the findings obtained, several directions for future research are proposed to further advance knowledge in this area. First, future studies should consider adopting a longitudinal research design to examine how the relationships between operator skills, raw material quality, automation accuracy, and dimensional accuracy evolve over time. Second, researchers are encouraged to expand the scope of the study by including additional variables that may influence dimensional accuracy. Factors such as machine maintenance practices, environmental conditions (e.g., temperature and vibration), process standardization, and organizational management practices could be incorporated to develop a more comprehensive model of manufacturing precision. Third, future research could employ mixed-methods approaches by combining quantitative analysis with qualitative methods such as interviews or case studies. This would allow for a deeper understanding of the practical challenges faced by machinists and workshop managers, as well as the contextual factors influencing decision-making in real-world settings. Fourth, comparative studies across different countries or industrial environments are recommended to help determine whether the findings of this study are context-specific or universally applicable. Fifth, future studies may explore interaction and moderating effects among the variables. Finally, there is a need for research focusing on technological advancements such as smart manufacturing, Industry 4.0 systems, and artificial intelligence in machining processes.

In conclusion, this study set out to examine the impact of operator skills, raw material quality, and automation accuracy on the dimensional accuracy of spare parts produced in Libyan oilfield workshops. Grounded in an integrated theoretical framework combining Human Capital Theory, the Resource-Based View, and Socio-Technical Systems Theory, the study adopted a quantitative, cross-sectional design to empirically test the proposed relationships. The findings revealed that all three independent variables have a significant positive influence on dimensional accuracy. The study contributes to both theory and practice by demonstrating that dimensional accuracy is not determined by a single factor but by the interaction of multiple system components. Improving dimensional accuracy in spare parts production requires a coordinated and strategic effort that aligns human capabilities, material resources, and technological systems. Such an integrated approach is essential for achieving sustainable performance and operational excellence in the oil and gas industry.

References

Adão, T., Gonzalez, D. G., & Magalhães, L. (2022). Using deep learning to detect the presence/absence of defects on leather: on the way to build an industry-driven approach. *Journal of Physics: Conference Series*.

Al-Dosary, A. S., & Rahman, S. M. (2005). Saudization (localization)—A critical review. *Human Resource Development International, 8*(4), 495–502.

Altintas, Y., Verl, A., & Brecher, C. (2011). Machine tool feed drives. *CIRP Annals, 60*(2), 779–796.

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89*(4), 369–406.

Arrazola, P. J., Özel, T., Umbrello, D., Davies, M., & Jawahir, I. S. (2013). Recent advances in modelling of metal machining processes. *CIRP Annals, 62*(2), 695–718.

Assad, S. W., & El Arnaout, N. (2019). Technical and vocational education and training in Libya: Current challenges and future directions. *International Journal of Educational Development, 70*, 102080.

Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of Management, 17*(1), 99–120.

Becker, G. S. (1964). *Human capital: A theoretical and empirical analysis, with special reference to education*. National Bureau of Economic Research.

Behr, D. (2017). Translating and adapting tests for cross-cultural assessments. In D. Matsumoto & F. J. R. van de Vijver (Eds.), *Cross-cultural research methods in psychology* (pp. 91–122). Cambridge University Press.

Binali, R., Kuntoğlu, M., Pimenov, D. Y., Usca, Ü. A., Gupta, M. K., & Korkmaz, M. E. (2022). Advance monitoring of hole machining operations via intelligent measurement systems: A critical review and future trends. *Measurement, 201*, 111757.

Bolarinwa, O. A. (2015). Principles and methods of validity and reliability testing of questionnaires used in social and health science researches. *Nigerian Postgraduate Medical Journal, 22*(4), 195–201.

Brinksmeier, E., Garbrecht, M., & Meyer, D. (2008). Machining induced residual stress and distortion of thin-walled parts. *CIRP Annals, 57*(1), 77–80.

Callister, W. D., & Rethwisch, D. G. (2018). *Materials science and engineering: An introduction* (10th ed.). Wiley.

Clegg, C. W. (2000). Sociotechnical principles for system design. *Applied Ergonomics, 31*(5), 463–477.

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

De Grip, A., & Van Loo, J. (2002). The economics of skills obsolescence: A review. In A. de Grip, J. van Loo, & K. Mayhew (Eds.), *The economics of skills obsolescence* (pp. 1–26). Emerald Group Publishing.

Deissinger, T. (2015). The German dual vocational education and training system as 'good practice'? *Local Economy, 30*(5), 557–567.

DeVellis, R. F. (2017). *Scale development: Theory and applications* (4th ed.). SAGE Publications.

Dreyfus, H. L., & Dreyfus, S. E. (1986). *Mind over machine: The power of human intuition and expertise in the era of the computer*. Free Press.

Elhakim, A., Hwang, J., Kim, S., Kim, E., & Kang, S. (2023). Three-dimensional accuracy of endodontic access preparations using novel nonrestrictive static guides: A laboratory study. *Australian Endodontic Journal*.

Ericsson, A., & Pool, R. (2016). *Peak: Secrets from the new science of expertise*. Houghton Mifflin Harcourt.

Farook, T., Ahmed, S., Giri, J., Rashid, F., Hughes, T., & Dudley, J. (2023). Influence of intraoral scanners, operators, and data processing on dimensional accuracy of dental casts for unsupervised clinical machine learning: An in vitro comparative study. *International Journal of Dentistry*.

Fitzgerald, B. (2020). Power quality issues in industrial applications: A review. *IEEE Transactions on Industry Applications, 56*(5), 5040–5049.

Fowler, F. J. (2014). *Survey research methods* (5th ed.). SAGE Publications.

Gonçalves, C. C., Malavolta, A., Barbosa, G., Shiki, S., & Parra, E. R. (2024). Influence of bed temperature on mechanical resistance, surface and dimensional quality of 3D printed parts by robotized fused pellet modeling. *Progress in Additive Manufacturing*.

Groover, M. P. (2020). *Fundamentals of modern manufacturing: Materials, processes, and systems* (8th ed.). Wiley.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). *Multivariate data analysis* (8th ed.). Cengage Learning.

Haslam, R. A., Waterson, P., & Cheyne, A. (2021). Human factors in manufacturing: A systematic review. *International Journal of Production Research, 59*(15), 4481–4510.

Jawahir, I. S., Brinksmeier, E., M'Saoubi, R., Aspinwall, D. K., Outeiro, J. C., Meyer, D., ... & Jayal, A. D. (2020). Surface integrity in material removal processes: Recent advances. *CIRP Annals, 69*(2), 1–33.

JLCCNC. (2024). How Precise Is CNC Machining Compared To Other Manufacturing Methods? https://jlccnc.com/blog/cnc-precision-comparison

Kalpakjian, S., & Schmid, S. R. (2014). *Manufacturing engineering and technology* (7th ed.). Pearson.

Koren, Y. (2020). The evolution of machine tool control and the advent of CNC. In Y. Koren (Ed.), *The global manufacturing revolution*. Wiley.

Krejcie, R. V., & Morgan, D. W. (1970). Determining sample size for research activities. *Educational and Psychological Measurement, 30*(3), 607–610.

Lall, S. (2000). Technological change and industrialization in the Asian newly industrializing economies. In L. Kim & R. R. Nelson (Eds.), *Technology, learning, and innovation* (pp. 13–68). Cambridge University Press.

Libyan Ministry of Labor and Rehabilitation. (2022). *Annual report on employment in the technical services sector*. Government Publication.

Maggiore, F., Thisted, E., Mouris, A., & Eivindson, T. (2022). Process optimization by real time analysis of liquids' composition in metal & mining. *TOS Forum*.

Mayr, J., Jedrzejewski, J., Uhlmann, E., Donmez, M. A., Knapp, W., Härtig, F., ... & Wegener, K. (2012). Thermal issues in machine tools. *CIRP Annals, 61*(2), 771–791.

National Oil Corporation (NOC). (2023). *Libya oil and gas industry workforce analysis*. Internal Industry Report.

Newaz, A. A., & Refat, J. (2025). Design and implementation of fixtures for milling, shaping and drilling operations. *American Journal of Mechanical Engineering*.

Pallant, J. (2020). *SPSS survival manual: A step by step guide to data analysis using IBM SPSS* (7th ed.). Routledge.

Pargeter, A. (2012). *Libya: The rise and fall of Qaddafi*. Yale University Press.

Peterka, J., Kuruc, M., Kolesnyk, V., Dehtiarov, I., Moravcikova, J., Vopat, T., ... & Simna, V. (2023). Selected Aspects of Precision Machining on CNC Machine Tools. *Machines, 11*(10), 946.

Polit, D. F., & Beck, C. T. (2012). *Nursing research: Generating and assessing evidence for nursing practice* (9th ed.). Lippincott Williams & Wilkins.

Pop, A. B., Titu, A. M., Ravai-Nagy, S., & Daraba, C. (2024). Influence of machining parameters on the dimensional accuracy of drilled holes in engineering plastics. *Polymers, 16*(11), 1490.

Powell, J. (2009). *The quality audit for ISO 9001:2008: A practical guide*. ASQ Quality Press.

Rajendran, N., Yurgel, C. C., Misiolek, W., & de Sousa, R. J. A. (2023). Hot forging die design optimization using FEM analysis for near-net forming of 18CrNiMo7-6 steel pinion shaft. *Metals*.

Rauner, F. (2007). Vocational education and training: A European perspective. In F. Rauner & R. Maclean (Eds.), *Rediscovering apprenticeship* (pp. 225-240). Springer.

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed.). Pearson.

Schwenke, H., Knapp, W., Haijtema, H., Weckermann, A., Schmitt, R., & Delbressine, F. (2008). Geometric error measurement and compensation of machines—An update. *CIRP Annals, 57*(2), 660-675.

Shahrum, M. A., Rajendran, T. K., Maidin, S., & Ismail, S. (2025). Process parameter optimization for dimensional accuracy of vacuum-assisted printed samples using response surface methodology. *Journal of Materials Engineering and Performance*.

Sirmon, D. G., Hitt, M. A., Ireland, R. D., & Gilbert, B. A. (2011). Resource orchestration to create competitive advantage: Breadth, depth, and life cycle effects. *Journal of Management, 37*(5), 1390-1412.

Sonntag, K. (2008). Produktivität und Humanisierung: Arbeitsgestaltung und Kompetenzentwicklung. In M. Kleinmann & B. Strauss (Eds.), *Potentiale der Personalpsychologie* (pp. 157–174). Hogrefe.

Stanton, J. V., Stanton, J. M., & Pires, G. (2011). Counterfeit products in the manufacturing supply chain. *Journal of Manufacturing Technology Management, 22*(8), 1026–1045.

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education, 2*, 53–55.

Tayier, W. (2024). Enhancing CNC precision: A review of geometric errors and simulation methods in three-axis CNC systems. *Journal of Engineering & Technological Advances, 9*(1), 55–74.

Teece, D. J. (2018). Business models and dynamic capabilities. *Long Range Planning, 51*(1), 40–49.

Tolio, T., Ceglarek, D., ElMaraghy, H. A., Fischer, A., Hu, S. J., Laperrière, L., ... & Wiendahl, H. P. (2013). SPECIES—Co-evolution of products, processes and production systems. *CIRP Annals, 62*(2), 629–652.

Trist, E. L., & Bamforth, K. W. (1951). Some social and psychological consequences of the longwall method of coal-getting. *Human Relations, 4*(1), 3–38.

Walker, G. H., Stanton, N. A., Salmon, P. M., & Jenkins, D. P. (2008). A review of sociotechnical systems theory: A classic concept for new command and control paradigms. *Theoretical Issues in Ergonomics Science, 9*(6), 479–499.

World Bank. (2023). *Libya economic monitor*. World Bank Group.

Yokoe, K., Aoyama, T., Fujishiro, T., Takeuchi, M., & Hasegawa, Y. (2022). An immersive micro-manipulation system using real-time 3D imaging microscope and 3D operation interface for high-speed and accurate micro-manipulation. *ROBOMECH Journal*.

Zhang, G., Liu, W., & He, Y. (2010). The impact of worker skill on manufacturing precision: An empirical study in the aerospace industry. *International Journal of Production Research, 48*(24), 7407–7424.

Zhang, K., Qiang, G., & Zhang, P. (2025). Study on the process of monolith NbTi wire with high N-value and high dimensional accuracy for NMR. *IEEE Transactions on Applied Superconductivity*.

Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T. (2017). Intelligent manufacturing in the context of industry 4.0: A review. *Engineering, 3*(5), 616–630.