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Improving coordinate measuring machine inspection efficiency through inspection-jig redesign: a lean-kaizen action research case study

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ABSTRACT

Coordinate Measuring Machines (CMMs) are widely used in precision manufacturing to verify dimensional accuracy and product conformity. Most studies on CMM efficiency focus on measurement strategy, probe-path optimisation, scanning, orientation, or digital inspection planning. Less attention has been given to the effect of fixture batch capacity on repeated loading and unloading. This study examines whether increasing inspection-jig capacity can reduce that handling requirement using a Lean-Kaizen, Plan-Do-Check-Act (PDCA), and action-research approach. The case study was carried out at a precision manufacturing company in Malaysia. Three jig concepts with capacities of 5, 20, and 49 cavities were assessed for capacity, CMM table fit, part location, probe accessibility, loading practicality, and fabrication feasibility. With the sampling requirement fixed at 216 parts per shift, the required loading/unloading cycles fell from 44 with the five-cavity jig to five with the 49-cavity jig, an 88.6% reduction in required handling cycles. Measurement-system adequacy was supported by prior Gage Repeatability and Reproducibility studies on the same CMM, with Total Gage R&R values of 5.97% and 9.56% of tolerance and 23 and 32 distinct categories for two representative characteristics. A targeted positional study was then conducted using the same reference part, removed and reseated at eight representative fixture locations (four

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corners, centre, and three intermediate positions) over five repeated rounds, giving 40 measurements. All readings were within the 3.310-3.330 mm drawing limits, and a randomized complete block analysis found no statistically significant fixture-position effect at alpha = 0.05 ($F(7,28) = 2.177$, $p = 0.0676$). The positional result applies to the eight tested locations and does not establish equivalence across all 49 cavities. Under an illustrative constant-cycle-time assumption of eight minutes per loading/unloading cycle, handling time would change from 352 to 40 minutes per shift. Because actual cycle duration was not measured after the redesign, this scenario does not establish whether handling time scales linearly or non-linearly with fixture density. The study therefore separates the direct cycle reduction from metrological evidence and scenario-based capacity implications.

Abbreviations

CMM	coordinate measuring machine
PDCA	Plan-Do-Check-Act
QA	Quality Assurance
GR&R	Gage Repeatability and Reproducibility
Cpk	Process capability index

1. INTRODUCTION

1.1 CMM inspection efficiency and fixture design

Coordinate measuring machines (CMMs) are widely used in precision manufacturing because they provide accurate, repeatable, and traceable dimensional information for complex mechanical features [1], [2]. Their effectiveness, however, is not determined by measurement capability alone. Inspection duration also depends on measurement strategy, probe travel, setup orientation, and the work required to load and unload parts [3-5]. In high-volume inspection, these supporting activities can consume substantial machine and operator time even when the measurement program itself is technically capable.

A substantial body of CMM research addresses efficiency through measurement planning. Recent path-planning studies focus on interference avoidance, probe posture, and efficient measurement sequences [6], [7]. Simulation and orientation-control studies also show that inspection quality and non-productive movement can be evaluated before execution [8], [9]. Intelligent CMM methods further reduce manual intervention in complex measurement tasks [10]. These developments improve how the CMM measures a component, but they do not necessarily remove inefficiency caused by the physical arrangement of parts on the table.

Inspection fixtures establish the location and restraint of the workpiece during measurement. Their design affects setup effort, accessibility, repeatability, and clamping risk [11-12]. Recent work also shows that setup planning and fixture design remain active engineering issues in automated inspection [13-14]. However, relatively few case studies quantify how CMM fixture capacity changes loading frequency for a fixed inspection workload.

1.2 Lean-Kaizen and structured improvement

Lean management offers a useful operational perspective because it distinguishes value-adding measurement from supporting activities that do not directly change the inspection result [15]. Recent manufacturing studies show that inspection performance can improve when the complete process is examined rather than the measurement step alone [16-18]. Metrology research similarly positions waste reduction as an important requirement for high-value manufacturing [19].

Kaizen contributes the participatory element required to develop a workable improvement. Recent studies emphasise employee involvement, standardisation, management support, and follow-through [20], [21]. Manufacturing cases also show that practical changes are more likely to be accepted when personnel close to the process participate in diagnosis and implementation [22-23]. This is important for inspection-jig redesign because the selected concept must satisfy inspection requirements, engineering constraints, probe access, operator handling, and fabrication capability at the same time.

The PDCA cycle provides a structured route from problem identification to implementation and sustainment [24-25]. Improvement is not complete when a concept is fabricated; it must also be checked, documented, assigned to an owner, and reviewed over time [26]. Action research is appropriate when researchers work with organisational participants to improve a real process [27-28], and recent manufacturing applications demonstrate its practical use in operational improvement [29].

1.3 Problem context, research gap and contribution

At the case company, the selected CMM process used a five-cavity jig for a fixed sampling requirement of 216 parts per shift. Based on fixture capacity, this required 44 loading and unloading cycles. Project records used an average planning value of eight minutes per loading/unloading cycle, giving an estimated handling burden of 352 minutes per shift. No repeated post-intervention time study was available, so the time-based values in this paper are treated as scenario estimates rather than measured means. The main operational comparison therefore focuses first on the number of handling cycles required by each fixture capacity.

The research gap concerns fixture batch capacity as an operational variable in CMM inspection. Previous studies have examined measurement paths, setup orientation, clamping, automation, and digital inspection planning, but there is less case-based evidence on how many parts can be presented in one setup and how this affects loading frequency for a fixed inspection workload. This study addresses that gap by comparing three jig configurations, selecting a higher-capacity design through cross-functional review, and calculating the change in required loading/unloading cycles while keeping the sampling requirement unchanged. The novelty is not a new CMM measurement algorithm, but a capacity-based way of reducing the non-measuring work around the measurement program.

Figure 1 brings together the main elements of the study. Lean is used to identify repeated handling as waste, Kaizen supports cross-functional participation, and PDCA guides implementation and sustainment. The framework also separates three types of evidence. The loading/unloading-cycle reduction is the direct capacity-based result. Measurement-system adequacy is considered separately through GR&R and post-intervention dimensional records, while released time and financial value are treated as scenario-based estimates. This distinction is important because a reduction in loading cycles does not by itself prove equivalent measurement reliability or an equal reduction in total inspection time.

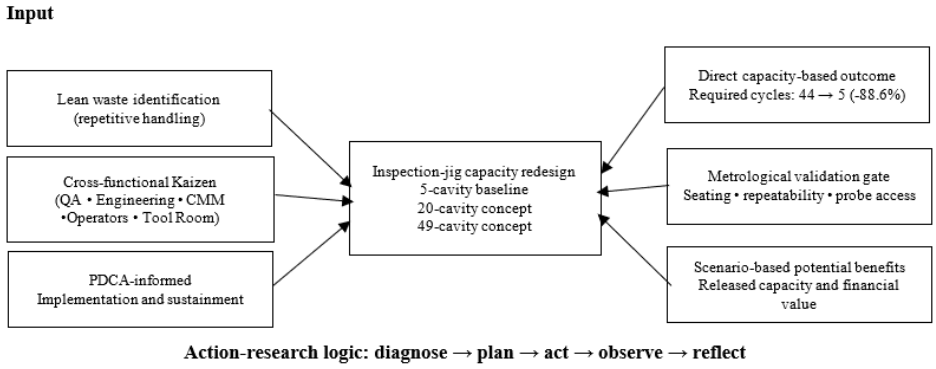


Fig 1. Conceptual framework linking inspection-jig capacity redesign with direct, validation-dependent, and scenario-based outcomes.

The study had four objectives: to identify the handling constraint created by the existing jig; to compare the 5-, 20-, and 49-cavity concepts using operational and technical feasibility criteria; to implement the selected design through a PDCA-informed action-research cycle; and to evaluate the cycle reduction, metrological evidence, and estimated released-capacity implications of the redesign. The contribution is case-based rather than universal. It shows how fixture capacity can be treated as a controllable inspection-process variable without replacing the CMM or changing the core measurement program, while keeping measurement validation as a separate requirement.

The framework also helps position the study against recent Industry 4.0 research. Digital measurement twins, predictive inspection, cognitive quality models, and digitally enhanced manufacturing frameworks offer important future possibilities [30-33]. The present work focuses on a lower-cost first step: improving the physical use of available inspection space before adding further software or automation.

2. METHODOLOGY

2.1 Research design, setting and participants

This study used an action-research case design within one CMM inspection process at a precision manufacturing company in Malaysia. The design suited the project because the team both investigated the operational constraint and implemented a change. The work involved diagnosis, development and evaluation of alternatives, implementation of the selected concept, observation of the outcome, and reflection on sustainment controls [27-28]. Qualitative operational evidence was combined with descriptive quantitative analysis: the qualitative evidence explained the handling problem and design decision, while the quantitative analysis calculated the change in required loading cycles and estimated related capacity implications.

The case boundary was the selected CMM inspection operation and its supporting activities. The fixed requirement was 216 sampled parts per shift. The project did not evaluate customer specifications, product performance, or other CMM processes. Operational information was supplied by personnel directly involved in the work, and no personal or customer-identifying data were used in the analysis. Table 1 summarises the cross-functional participants and the evidence contributed by each group.

Table 1. Participants and roles in the improvement project

Participant group	Number	Role and evidence contributed
QA supervisor	1	Inspection requirements, process expectations, and quality review
QA engineer	1	Process analysis, baseline confirmation, and validation input
Engineering representative	1	Design feasibility, table fit, and mechanical considerations
CMM programmers	2	Probe access, path compatibility, and program feasibility
Operators	4	Loading sequence, handling practicality, and usability feedback
Tool-room representative	1	Jig fabrication, modification, and manufacturing feasibility

2.2 Action-research cycle and evidence collection

The research followed the diagnose-plan-act-observe-reflect action-research cycle shown in Figure 2. PDCA was used to guide implementation and sustainment, but it was not treated as identical to the research cycle. During diagnosis, the team observed the repeated loading sequence and confirmed the fixed sampling requirement. In the planning stage, the existing jig and two higher-capacity concepts were compared using operational and technical criteria. The act stage involved in-house fabrication and operating trials of the selected 49-cavity design. Observation covered table fit, loading practicality, program accessibility, the required loading-cycle count, and the available post-intervention dimensional evidence. Reflection focused on whether the operational improvement was supported by sufficient measurement evidence and what controls were still needed for sustainment.

Five sources of evidence were used: direct observation of the existing workflow; inspection, sampling, and project records; design information for the three concepts; cross-functional discussions; and measurement-system and post-intervention dimensional records. The metrological evidence included an existing GR&R study for the selected product, post-intervention dimensional readings, and production-capability records from the same CMM. These sources were used to keep operational calculations, measurement evidence, and scenario assumptions separate. The cross-functional discussions were part of normal project work rather than formal research interviews, so they are reported as qualitative operational input rather than transcript-based thematic analysis.



Fig 2. Diagnose-plan-act-observe-reflect action-research cycle used in the study; PDCA informed implementation and sustainment.

The relationship between the study objectives, evidence sources, and analysis is shown in Table 2.

Table 2. Evidence and analysis used in the study

Study focus	Primary evidence	Analysis
Existing operational inefficiency	Observation, sampling records, operator input	Process mapping and identification of repeated handling
Selection of a feasible redesign	Concept drawings, table dimensions, cross-functional discussions	Qualitative comparison of capacity, fit, access, and practicality
Capacity-based operational effect	Sampling requirement and jig capacity	Cycle requirement calculation and percentage change
Scenario-based capacity and financial implication	Project time, labour-rate, and machine-rate assumptions	Scenario calculation using project assumptions; reported separately from direct findings
Metrological adequacy	GR&R study, post-intervention dimensional records, production capability records, targeted same-part positional study	GR&R interpretation, descriptive statistics, specification conformance, Cpk review, and blocked ANOVA for fixture position
Sustainment requirements	Stakeholder reflection and literature	Identification of standard work, training, ownership, maintenance, and review needs

2.3 Design requirements and concept evaluation

The redesign aims to increase the number of parts presented in each loading cycle without changing the CMM system or the fixed sampling requirement. Capacity alone was not enough. Each concept also had to fit within the usable CMM table area, locate and orient the parts consistently, allow sufficient probe access, remain practical for loading and unloading, and be feasible for in-house fabrication. These conditions were checked before the possible reduction in handling cycles was considered. Detailed fixture photographs and design drawings are not reproduced in this article because they contain proprietary manufacturing information.

The existing five-cavity jig was used as the baseline. Its part location and compatibility with the existing inspection program were already established through routine use. However, its low capacity required frequent loading and unloading and used only a limited part of the available inspection area. It therefore served as the reference configuration for the redesign. The 20-cavity concept provided an intermediate option. For the fixed workload of 216 parts, it would require 11 loading/unloading cycles. The cross-functional review found that it reduced handling repetition compared with the baseline, but it still left more of the usable table area unused than the 49-cavity layout. It was therefore considered feasible but was not selected for implementation.

The 49-cavity concept used more of the available table area and reduced the calculated loading requirement to five cycles. Because of the higher fixture density, the team considered table fit, part seating and orientation, probe accessibility, loading practicality, and fabrication feasibility. Operating trials confirmed physical fit and that the existing inspection program could access the required measurement features. However, the project records did not contain numerical minimum Z-axis clearance, probe-extension margins, or a cavity-by-cavity collision-clearance map. Program accessibility is therefore reported as an operational trial result rather than a quantified clearance study. Measurement-system adequacy was evaluated separately using the GR&R and post-intervention dimensional evidence described in Sections 2.5 and 3.3.

The concepts were selected through a qualitative, cross-functional review rather than a weighted scoring model. The team first checked the mandatory feasibility conditions: CMM table fit, repeatable part location, probe and program access, loading practicality, and fabrication feasibility. For concepts that passed this screening, batch capacity, use of the available inspection area, and the resulting number of loading cycles were then compared. QA reviewed the inspection requirements, Engineering reviewed dimensions and mechanical fit, CMM programmers assessed program and probe access, operators considered handling practicality, and the tool room reviewed fabrication feasibility. The final choice was made by technical consensus. Table 3 records the criteria that were actually used rather than adding a numerical score after the project was completed.

Table 3. Qualitative comparison of the inspection-jig concepts

Criterion	**5-cavity baseline**	**20-cavity concept**	**49-cavity concept**
Parts per setup	5	20	49
Required cycles for 216 parts	44	11	5
Use of available table area	Limited	Partial	Highest
Physical fit within CMM table envelope	Existing and proven	Reviewed at concept stage	Confirmed in operating trial
Part location / seating requirement	Existing and proven	Required confirmation	Reviewed; formal repeatability validation required
Probe accessibility / program compatibility	Existing and proven	Required confirmation	Operationally confirmed; numerical Z-axis clearance and probe-extension margin not recorded
Loading and handling practicality	Highest repetition	Moderate repetition	Lowest required cycle count; trialled for practicality
Fabrication feasibility / status	Existing process	Concept only	Fabricated in-house

Key technical concern	Low capacity	Residual unused area	Dense-layout repeatability, seating, clearance, and collision risk
Decision	Baseline	Not selected	Selected for intervention

2.4 Intervention, operational measures and calculation basis

After the 49-cavity concept was selected, the in-house tool room fabricated the jig and it was trialled under operating conditions. The trial checked table fit, loading practicality, and program accessibility. The comparison with the five-cavity baseline used the same sampling requirement of 216 parts per shift so that any change in the calculated loading-cycle requirement came from fixture capacity rather than a different workload. Measurement-system adequacy was assessed separately using the GR&R and post-intervention dimensional records described in Section 2.5.

The number of loading/unloading cycles was calculated by dividing the fixed sampling requirement by jig capacity and rounding up to the next whole cycle. The five-cavity jig required 216/5 = 43.2, or 44 cycles. The 49-cavity jig required 216/49 = 4.41, or 5 cycles. The change from 44 to 5 cycles was therefore an 88.6% reduction in the number of required handling cycles. This is a capacity-based result and should not be interpreted as a measured 88.6% reduction in total CMM inspection time or overall CMM efficiency.

Project records used approximately eight minutes for each loading/unloading cycle. This value was applied to both configurations only as an illustrative constant-cycle-time scenario. It does not assume that handling time per part scales linearly with fixture capacity. Actual cycle duration may change non-linearly as cavity count increases because of reach distance, part sorting, loading sequence, dense clearances, and operator fatigue. Since no repeated post-intervention time-and-motion study was available, the estimated 40 minutes for the 49-cavity setup and the associated released hours are scenario values rather than measured outcomes that may overstate the benefit if the denser layout requires longer handling per cycle.

2.5 Measurement-system, positional, and post-intervention validation

Four types of metrological evidence were used to evaluate measurement performance after increasing fixture density. First, an existing GR&R study for the selected product was carried out on the same CMM used for post-intervention verification. The study used 10 samples, two appraisers, and two repeated measurements per sample. Two representative characteristics were evaluated: 2.10 +/- 0.02 mm and 3.32 +/- 0.01 mm. Under the company's measurement-system criteria, less than 10% of tolerance is rated as very good, 10%-30% is conditionally acceptable, and at least five distinct categories are required.

Second, post-intervention production records from the redesigned inspection arrangement were reviewed for two characteristics measured on the same CMM. Fifteen readings were available for each characteristic and involved three inspectors. The drawing limits were 3.304-3.324 mm for the 3.314 mm characteristic and 1.984-2.024 mm for the 2.004 mm characteristic. The tighter values shown on the internal-control labels were not used as the drawing limits. The readings were summarised by mean, sample standard deviation, observed range, and specification conformance.

Third, a 72-reading production-capability record from the same CMM was reviewed for the same two monitored characteristics using the drawing specification limits. These records were used as supporting process-capability evidence. Fourth, following the second-round review, a targeted fixture-position study was carried out for the 3.32 +/- 0.01 mm characteristic. The same reference part was removed and reseated

before every measurement at eight representative fixture locations: the four corners, the centre, and three intermediate positions. Five repeated rounds were completed at each position, giving 40 measurements. The measurement sequence varied by round to reduce confounding between fixture position and measurement order.

For the targeted positional study, results were summarised by position mean, sample standard deviation, range, and specification conformance. A randomized complete block analysis of variance was used with fixture position as the treatment factor and measurement round as the block. The test assessed whether a statistically detectable position effect was present across the eight sampled locations at alpha = 0.05. Because only eight representative locations were sampled, the analysis was treated as targeted positional validation rather than proof of equivalence across all 49 cavities.

2.6 Data analysis and research quality

Qualitative evidence was grouped into four themes: handling frequency, use of inspection space, technical feasibility, and sustainment requirements. The quantitative analysis combined descriptive calculations with targeted positional validation. The main direct operational metric was the percentage change in required loading/unloading cycles. GR&R was interpreted using percentage of tolerance, variance contribution, and number of distinct categories. The 15 post-intervention readings were summarised by mean, sample standard deviation, range, and conformance to specification, while the 72-reading Cpk values were used as supporting capability indicators. For the targeted position study, mean and within-position variation were calculated for each of eight locations, and a randomized complete block ANOVA tested the fixture-position effect while controlling for measurement round. Estimated handling time, operator-hours, and released-capacity value were kept separate as scenario-based indicators rather than measured performance outcomes.

Credibility was supported by triangulating several data sources, reviewing the findings across functions, and using consistent definitions before and after the intervention. The audit trail included the fixed sampling requirement, jig capacities, concept alternatives, feasibility criteria, calculation basis, GR&R report, post-intervention dimensional records, production-capability records, and the targeted eight-position same-part remove-and-reseat study. The paper separates the evidence into three levels: the direct capacity-based cycle calculation, the metrological evidence, and the assumption-based time and financial estimates. The positional study strengthens the metrological evidence for representative locations while avoiding a claim of equivalence for every one of the 49 cavities.

3. RESULTS AND DISCUSSION

The results are presented in the same order as the study objectives: the baseline handling constraint, selection of the 49-cavity concept, the direct cycle reduction, the measurement-system evidence and targeted positional validation, the scenario-based released-capacity value, and the engineering implications of the redesign.

3.1 Baseline condition and selection of the 49-cavity concept

The baseline analysis showed that the main operational constraint is the number of loading and unloading events required by the five-cavity jig. For a fixed workload of 216 parts, 44 cycles were required.

Each cycle involved repeated part placement and removal around the measurement program. From a Lean perspective, the redesign therefore targeted the frequency of these handling events rather than the CMM measurement algorithm or measurement speed.

The 20-cavity concept reduced the calculated cycle requirement to 11 but did not use the available table area as fully as the larger layout. The 49-cavity design was selected because it gave the lowest cycle requirement among the concepts that passed the cross-functional feasibility review. The decision was not based on capacity alone. QA reviewed the inspection requirements, Engineering checked arrangement and fit, programmers assessed probe and program access, operators considered handling practicality, and the tool room reviewed fabrication feasibility. Measurement-system adequacy and representative fixture-position consistency were then checked using the GR&R, post-intervention dimensional evidence, and targeted same-part positional validation reported in Section 3.3.

This collaborative process is consistent with the recent Kaizen's literature, which emphasises participation by personnel close to the process during diagnosis and solution development [20], [22]. It also supports the practical value of integrating fixture and inspection planning [11]. The case adds a capacity perspective by showing how the number of fixture locations influences the surrounding inspection workflow.

3.2 Capacity-based reduction in required loading/unloading cycles

Table 4 separates the direct loading-cycle result from the estimated handling-time and operator-hour effects. Figure 3 shows only the required loading/unloading cycles so that the direct capacity result is not visually mixed with the assumption-based time estimates. The estimated handling time and operator-hours are reported separately in Table 4 as scenario values.

This finding complements recent studies that improve CMM performance through measurement strategy, path planning, and automated inspection planning [3], [5], [7]. Those studies mainly focus on how measurement is executed. The present case examines a different part of the inspection process: how many parts are presented to the CMM in each loading event. It is also consistent with fixture-planning studies, showing that workholding and setup decisions affect inspection accessibility and batch processing [11], [13], [14].

Table 4. Capacity-based cycle result and scenario-based time implications of the 49-cavity jig

Metric	5-cavity jig	49-cavity jig	Change / interpretation
Sampling requirement	216 parts	216 parts	Fixed workload
Jig capacity	5 parts	49 parts	+880% fixture capacity per setup
Required loading/unloading cycles	44	5	-39 cycles (-88.6%); direct capacity-based result
Estimated handling time*	352 min	40 min	-312 min (-88.6%); illustrative constant-cycle-time scenario only
Estimated operator time*	5.87 h	0.67 h	-5.20 h (-88.6%); scenario only, not measured

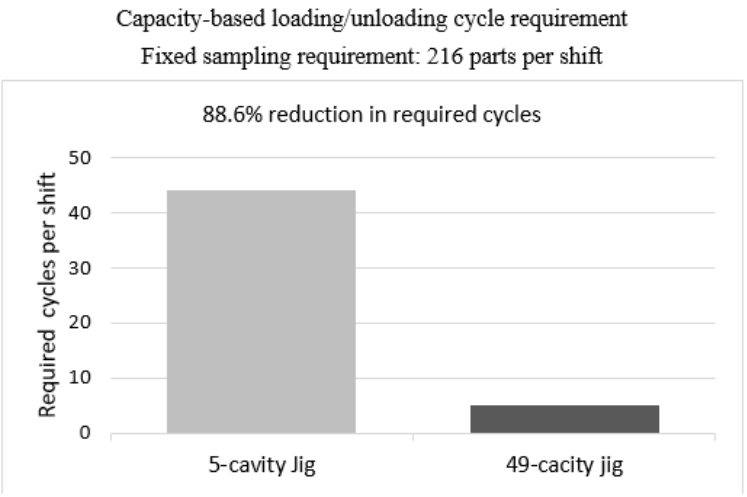


Fig. 3. Capacity-based reduction in required loading/unloading cycles for a fixed sampling requirement of 216 parts per shift.

Applying the same eight-minute planning assumption to both configurations gives an illustrative handling-time change from 352 to 40 minutes per shift. This should not be interpreted as evidence that handling time scales proportionally with the number of cycles. A 49-cavity loading event may require more time than a five-cavity event because of reach distance, part sorting, loading sequence, dense spacing, and fatigue. Repeated time-and-motion observations are therefore required to determine whether the actual relationship between fixture density and handling time is linear or non-linear.

3.3 Measurement-system adequacy and targeted positional validation

The formal GR&R study showed acceptable measurement-system performance for both representative characteristics. For the 2.10 ± 0.02 mm characteristic, Total Gage R&R was 5.97% of tolerance, variance contribution was 0.35%, and the number of distinct categories was 23. For the 3.32 ± 0.01 mm characteristic, Total Gage R&R was 9.56% of tolerance, variance contribution was 0.19%, and the number of distinct categories was 32. Both characteristics met the organisation's criterion of less than 10% of tolerance and exceeded the minimum requirement of five distinct categories. The detailed study also reported negligible appraiser-to-appraiser reproducibility variation, indicating that most of the observed gage variation came from repeatability rather than differences between appraisers.

Post-intervention verification on the same CMM provided additional evidence after the higher-capacity jig was implemented. Fifteen readings were reviewed for each of two characteristics, with measurements involving three inspectors. For the 3.314 mm characteristic with drawing limits of 3.304-3.324 mm, the mean was 3.31353 mm, the sample standard deviation was 0.00074 mm, and the observed range was 3.312-3.315 mm. For the 2.004 mm characteristic with drawing limits of 1.984-2.024 mm, the mean was 2.01020 mm, the sample standard deviation was 0.00257 mm, and the observed range was 2.005-2.014 mm. All 15 readings for both characteristics were within the applicable drawing limits.

To directly examine the fixture-position concern, a targeted validation was performed using the same reference part across eight representative positions: four corners, the centre, and three intermediate locations. The part was removed and reseated before every measurement, with five repeated rounds per position, for 40 measurements in total. All 40 readings were within the 3.310-3.330 mm drawing limits. Position means ranged from 3.3122 to 3.3136 mm, and the largest difference between position means was 0.0014 mm, equivalent to 7.0% of the 0.020 mm tolerance. The overall mean was 3.312925 mm with an overall sample standard deviation of 0.000797 mm. A randomized complete block ANOVA, with measurement round treated as the block, did not detect a statistically significant fixture-position effect at alpha = 0.05 ($F(7,28) = 2.177$, $p = 0.0676$).

The 72-reading production-capability records from the same CMM provided further context. Using the confirmed drawing limits, the recorded Cpk values were 2.895 for the 3.314 mm characteristic and 2.790 for the 2.004 mm characteristic. These values indicate a capable process and support the post-intervention dimensional results from the same measurement equipment. However, the records were not organised as repeated measurements of the same reference part at all 49 fixture positions, so they are used as supporting evidence rather than direct proof of position-to-position repeatability.

Overall, the GR&R results support the underlying measurement system, the production records show conforming measurements for the characteristics reviewed, and the targeted same-part remove-and-reseat study provides direct evidence across representative fixture locations. No statistically significant position effect was detected among the eight tested corner, centre, and intermediate locations. However, eight of the 49 cavities were sampled; therefore, the study supports positional consistency for the tested locations but does not claim statistical equivalence of all 49 cavities. Localised effects at untested cavities cannot be ruled out.

Table 5. Measurement-system, post-intervention, and targeted positional validation evidence

Evidence	Characteristic / specification	Key result	Interpretation
GR&R	2.10 ± 0.02 mm	5.97% of tolerance; 0.35% contribution; ndc = 23	Acceptable measurement system; not a 49-position fixture repeatability test
GR&R	3.32 ± 0.01 mm	9.56% of tolerance; 0.19% contribution; ndc = 32	Acceptable measurement system; not a 49-position fixture repeatability test
Post-intervention verification	3.314 mm; 3.304-3.324 mm	n = 15; mean 3.31353; SD 0.00074; range 3.312-3.315	Within drawing limits; normal production verification, not position-to-position repeatability
Post-intervention verification	2.004 mm; 1.984-2.024 mm	n = 15; mean 2.01020; SD 0.00257; range 2.005-2.014	Within drawing limits; normal production verification, not position-to-position repeatability
Production capability	3.314 mm; 3.304-3.324 mm	n = 72; Cpk = 2.895	Supporting process capability evidence; not position-specific
Production capability	2.004 mm; 1.984-2.024 mm	n = 72; Cpk = 2.790	Supporting process capability evidence; not position-specific
Targeted positional validation	3.32 +/- 0.01 mm; 8 representative positions	n = 40; 5 repeats/position; position-mean spread = 0.0014 mm (7.0% tolerance); $F(7,28) = 2.177$; $p = 0.0676$	40/40 within limits; no statistically significant position effect detected across the eight tested locations

3.4 Scenario-based released-capacity value

The annual scenario uses 528 operating shifts per year, calculated as 22 operating days per month × 2 shifts per day × 12 months. The estimated 5.20 hours released per shift is valued separately using the labour rate and the CMM machine rate. These are alternative valuation perspectives applied to the same scenario hours and must not be added together. The previous combined gross indicator has therefore been removed.

Table 6. Scenario-based annual released-capacity values

Financial item	Value	Interpretation
Operating basis	528 shifts/year	22 operating days/month × 2 shifts/day × 12 months
Labour rate	USD 3.59/h	Project input assumption
CMM machine rate	USD 4.69/h	Project input assumption
Estimated time released	5.20 h/shift	Constant-cycle-time scenario; not measured
Annual labour-capacity value	USD 9,856.70	Alternative labour-capacity valuation; not payroll saving
Annual machine-capacity value	USD 12,876.86	Alternative machine-capacity valuation; not realised cash saving

3.5 Interpretation through the socio-technical framework

The first expectation was that a higher-capacity jig would reduce the number of repeated handling events needed for the fixed workload, and the capacity calculation supports this. The GR&R results of 5.97% and 9.56% of tolerance, with 23 and 32 distinct categories, support the underlying measurement system for the representative characteristics. The post-intervention production data remained conforming, and the targeted same-part positional study added direct evidence across four corner locations, the centre, and three intermediate positions. All 40 positional-study readings were within specification, and no statistically significant fixture-position effect was detected at alpha = 0.05. This strengthens the metrological basis for the redesign while limiting the conclusion to the eight tested locations rather than all 49 cavities.

Cross-functional Kaizen participation was also important to the design decision. No single function had all the information needed to assess the redesign. Inspection requirements, mechanical fit, probe and program access, loading practicality, and fabrication capability were reviewed by the teams responsible for those areas. This reduces the risk of choosing a high-capacity design that looks attractive operationally but could not be used reliably in practice.

The project also illustrates the role of structured continuous improvement. The research followed the diagnose-plan-act-observe-reflect cycle, while PDCA guided implementation and sustainment. Diagnosis, planning, fabrication, operating trials, the capacity calculation, measurement-system review, and reflection were completed. The GR&R and post-intervention records strengthen the technical basis for the redesign. Full standardisation, however, still requires updated work instructions, operator training, assigned maintenance ownership, periodic review, and continued checks on seating, contamination, fixture wear, and probe clearance [24], [26].

3.6 Scientific contribution and relation to previous studies

The scientific contribution of this case is deliberately narrow. It does not introduce a new CMM algorithm, probe strategy, or uncertainty model. Instead, it treats fixture batch capacity as an operational design variable that affects the number of handling events needed for a fixed inspection workload. This complements recent work on measurement-time estimation, automated inspection planning, and probe orientation [3], [7], [9], as well as fixture and clamping studies concerned with accessibility, restraint, and automated fixture design [11], [12], [14]. The present study makes the capacity-to-handling relationship explicit while keeping metrological validation as a separate requirement.

The contribution can also be viewed at the interface between Lean and metrology. Lean identifies repeated loading as non-value-added supporting work, while metrology limits how far fixture density can be increased without affecting seating, restraint, accessibility, or repeatability. The 49-cavity redesign demonstrates the operational side through the 44-to-5 cycle calculation. The metrological side is supported by acceptable GR&R results, conforming post-intervention records, and a targeted same-part remove-and-reseat study across eight representative fixture locations. The absence of a statistically significant position effect in this targeted study strengthens the case for the redesign, while the sampling of eight rather than all 49 cavities defines the boundary of the claim.

3.7 Practical engineering implications

Other manufacturers can apply the same basic sequence when inspection capacity appears constrained. First, separate the CMM measurement program from the loading, unloading, setup, and waiting activities around it. Second, identify whether the main constraint comes from measurement strategy, probe movement, fixture capacity, or operator method. Third, develop alternative layouts and check them against both productivity and metrological requirements. Fourth, trial the selected concept for physical fit, program access, and operator practicality. Fifth, verify the underlying measurement system and perform targeted positional checks using the same reference part at representative centre, edge, corner, and intermediate locations before standardisation. Actual time savings should only be quantified after enough repeated time observations have been collected.

This sequence is useful for organisations that might otherwise respond to inspection backlogs by purchasing another CMM. Additional equipment may be justified in some cases, but unused table area and repeated handling should first be checked as possible constraints. In this case, fixture redesign substantially reduced the number of required loading events without changing the CMM itself. Whether this produces the same level of time or financial benefit depends on the actual handling-time distribution, the measurement validation, and how the released capacity is used.

The redesign also creates a platform for later digital improvement. Once the physical layout is stable, the setup can be combined with digital measurement twins, predictive inspection, cognitive quality models, and digitally enhanced manufacturing frameworks [30-33]. Physical and digital improvement should therefore be viewed as complementary rather than competing approaches.

3.8 Limitations and future work

This study reports one intervention in one CMM process at one manufacturing site. The findings therefore support analytical learning rather than statistical generalisation to all components, fixtures, or machines. The two configurations were compared descriptively without a control group or inferential analysis. The strongest demonstrated operational result is the capacity-based reduction in required loading/unloading cycles for the fixed sampling workload. The metrological evidence supports the redesign but is narrower in scope.

The handling-time estimate uses the same eight-minute planning value for both configurations because no repeated post-intervention time study was available. It therefore cannot establish whether handling duration changes linearly or non-linearly as fixture density increases. Reach distance, part sorting, loading sequence, dense clearances, and operator fatigue may add non-linear overhead. From a metrology perspective, the targeted position study substantially strengthens the validation by testing the same reference part after repeated removal and reseating at four corners, the centre, and three intermediate locations. Nevertheless, only eight of 49 cavities were sampled, and the p-value of 0.0676 should be interpreted as failure to detect a significant position effect at alpha = 0.05 rather than proof that all cavities are equivalent. Numerical Z-axis clearance and probe-extension margins were also not retained in the project records. Ergonomics, long-term durability, contamination risk, and maintenance requirements were not quantified.

Future work could extend the targeted positional validation to a larger proportion of the 49 cavities, particularly positions with the greatest reach, edge proximity, or suspected seating sensitivity, and could repeat the study under different thermal conditions if temperature effects are a concern. Repeated time-and-motion observations should also be collected at both fixture capacities to determine the actual relationship between cavity count and handling time. Future validation should additionally document minimum Z-axis clearance, probe-extension margin, and collision risk at difficult-to-access positions, together with long-term checks for fixture wear, contamination, seating errors, and maintenance needs.

4. CONCLUSION

This action-research case examined inspection-jig capacity as a source of repeated handling in an existing CMM process. For the fixed sampling requirement of 216 parts per shift, the five-cavity baseline required 44 loading/unloading cycles, while the selected 49-cavity jig required five cycles on a capacity basis. The demonstrated operational result is therefore an 88.6% reduction in the number of required loading/unloading cycles. This result refers to handling frequency and should not be read as an experimentally measured 88.6% reduction in total CMM inspection time or overall CMM efficiency.

The measurement evidence supports the underlying CMM measurement system and provides direct targeted validation of representative fixture positions. Formal GR&R results were 5.97% and 9.56% of tolerance, with 23 and 32 distinct categories. In the targeted same-part study, the reference part was removed and reseated across eight representative positions over five repeated rounds, giving 40 measurements. All readings were within the 3.310-3.330 mm drawing limits; position means differed by at most 0.0014 mm (7.0% of tolerance), and no statistically significant fixture-position effect was detected at alpha = 0.05 ($F(7,28) = 2.177$, $p = 0.0676$). These results support positional consistency for the eight tested locations but do not establish statistical equivalence across all 49 cavities.

Under the illustrative constant-cycle-time assumption of eight minutes per loading/unloading cycle, handling time would change from 352 to 40 minutes per shift, equivalent to 5.20 hours of scenario-based released capacity per shift. Because actual cycle duration was not measured after the redesign, these values do not establish linear or non-linear handling-time scaling. On an annual basis of 528 operating shifts, labour-capacity and machine-capacity values are reported separately as alternative valuation perspectives and are not combined. Overall, the study links fixture batch capacity to handling frequency while clearly separating the demonstrated cycle reduction from measurement-system evidence and scenario-based capacity estimates.

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6. CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. AUTHORS' CONTRIBUTIONS

Ooi Phei Leng: Conceptualisation, methodology, project administration, writing, review and editing.

Mohamad Faiz Bin Sani: Data curation, formal analysis, and visualisation.

Sherry Ameera Binti Mustaffa @ Sulaiman: Investigation, documentation, writing and editing.

Mohamad Amirul Ain Bin Sakila: Literature review and conceptual framework.

Khamaleshvarman A/L Ballasingam: Interpretation, limitations, and recommendations.

Beni Widarman Bin Yus Kelana: Supervision, reviewing and validation.

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation and revision of this work, the authors used ChatGPT (OpenAI) to assist with language refinement, readability, formatting, and organisation of the manuscript and reviewer responses. All technical content, calculations, statistical results, references, interpretations, and conclusions were reviewed and verified by the authors. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content, accuracy, and integrity of the publication.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request, subject to the confidentiality requirements of the participating company.

10. ETHICS STATEMENT

This study did not involve human or animal subjects as research participants. Cross-functional personnel contributed operational input as part of normal workplace improvement activities, and no personal or customer-identifying data were collected or analysed.

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