Journal of Management Science Research Review
https://jmsrr.com/index.php/Journal/about

Volume. 4 Issue No. 4 (2025)

Online ISSN: 3006-2047
Print ISSN: 3006-2039

INTEGRATING LEAN MANUFACTURING AND ERGONOMICS FOR SUSTAINABLE WORKFORCE EFFICIENCY IN THE ERA OF INDUSTRY 5.0

Faiza Hisbani*
Meharn University of Engineering and technology jamshoro.
Email : faizahisbani@gmail.com

Dr Mohammad Moinuddin Qazi Abro
University technology Federal UTF Parana parto Branco Brazil
Email : qaziabro@gmail.com

Dr shakil Ahmed sheikh
Mehran University of Engineering and technology jamshoro
Email : shakeel.shaikh@faculty.muet.edu.pk

Abstract

Background Industry 5.0 emphasizes human-centric, resilient production, yet lean transformations can inadvertently raise musculoskeletal risk if ergonomics is not embedded. We evaluated an “ErgoLean” approach that integrates participatory ergonomics into value-stream improvement to test whether wellbeing and operational performance can improve together. **Methods:** We ran a pragmatic before–after field study with 130 matched operators on manual/hybrid workstations. The intervention combined annotated value-stream mapping (with step-level RULA/REBA/HAL indicators), co-design workshops, and piloted workstation/flow changes (adjustable fixtures, part presentation, lighting/visual aids, error-proofing, and micro-breaks) institutionalized through daily management. Outcomes were measured pre-intervention and after stabilization: ergonomic exposure (RULA, REBA, HAL; composite 0–1 index), Nordic Musculoskeletal Questionnaire (NMQ) discomfort index, workplace organization (5S audit), single-piece cycle time, aggregated defect rate, and Work Ability Index (WAI). Paired t-tests assessed within-person change; a 2×2 chi-square compared defect rates; effect sizes used Cohen’s d_z. **Results:** Ergonomic exposure decreased across all instruments: RULA −0.88 (−18.7%), REBA −1.29 (−17.1%), HAL −0.76 (−14.9%), and composite −0.040 (−7.8%), all $p < 10^{-12}$. NMQ discomfort declined −0.88 (−17.2%; $p \approx 1.6\times10^{-32}$). Workplace organization improved +12.02 points on 5S (+19.2%; $p \approx 8.3\times10^{-52}$). Flow accelerated with cycle time −5.09 s (−9.8%; $p \approx 2.0\times10^{-43}$) and narrower dispersion. Quality improved concurrently: defects fell from 1.845% to 1.158% (risk ratio 0.63, 95% CI 0.54–0.73; $\chi^2 \approx 39.2$, $p \approx 3.9\times10^{-10}$). WAI increased +1.62 (+4.6%; $p \approx 9.7\times10^{-32}$). Effect sizes were large for most endpoints (e.g.,

$d_z \approx 1.84$ for cycle time; 2.22 for 5S; 1.59, 1.54, and 1.36 for RULA, REBA, HAL; 1.41 for NMQ; 1.38 for WAI). **Conclusions:** Embedding ergonomics into value-stream design and governance produced sizeable, precise, and directionally consistent improvements in exposure, symptoms, organization, flow, quality, and perceived work ability supporting joint optimization of wellbeing and performance rather than a trade-off. The ErgoLean pattern offers a practical pathway to human-centric resilience in Industry 5.0 settings.
Keywords: ErgoLean; Industry 5.0; participatory ergonomics; value-stream mapping; RULA; REBA; HAL; Nordic Musculoskeletal Questionnaire; 5S; cycle time; defect rate; Work Ability Index; human-centred manufacturing; lean.

Introduction

Manufacturing is pivoting from the efficiency-first logic of late Industry 4.0 to the human-centric, resilient, and sustainable ethos of Industry 5.0 where human capability, safety, and wellbeing are treated as strategic assets [1]. In this context, integrating lean with ergonomics an **Ergo Lean** approach offers a pragmatic path to align operational excellence with worker health in manual and hybrid manual–automated settings common to pharmaceutical, food, and light engineering sectors in emerging economies [2].

Lean methods (VSM, standardized work, 5S, SMED, visual management) reliably cut waste and variation, yet gains are uneven when human factors are not designed into analysis and change [3]. Ergonomics provides mature instruments RULA, REBA, HAL, NMQ, NASA-TLX, WAI to quantify physical and cognitive demands, but improvements often stay local and decouple from flow redesign [4–5]. This misalignment can intensify repetition or reach when takt is shortened without concurrent changes in layout, tooling, or methods, creating a paradox of higher throughput alongside rising WMSD risk and error [5,7–8]. Conversely, early ergonomic integration task simplification, assistive fixtures, adjustability, illumination, error-proofing can reduce motion waste *and* biomechanical stressors because both share root causes in layout, reach, and method [9–10].

Prior work shows that lean's human outcomes vary with design quality, participatory depth, and the metrics used to steer improvement; participatory ergonomics enhances adoption but often fails to quantify system-level flow effects; and digital tools are frequently piloted without adequate change management [10–12]. What is missing is a **simple, deployable method** that helps resource-constrained plants (i) see where risk and waste co-locate,

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

(ii) co-design interventions that protect takt, and (iii) verify that wellbeing and performance move together.

This study introduces an Ergo Lean methodology that couples a standardized mixed-methods baseline (RULA, REBA, HAL; NMQ, NASA-TLX, WAI; cycle-time distributions, changeover, FPY/OEE) with a VSM annotated by ergonomic indicators, participatory gemba workshops to generate and prioritize changes, lightweight simulation to de-risk sequencing, and daily management to lock in gains [13–18]. The contributions are: (1) a usable diagnostic that links ergonomic exposure to flow performance; (2) an extension of VSM from annotation to a **prioritization engine** for joint optimization; and (3) an execution pattern that combines participatory design with simulation for faster, safer implementation [19–22].

Research Questions (RQs)

- **RQ1:** Can an Ergo Lean intervention simultaneously reduce ergonomic risk (RULA/REBA/HAL) and improve operational performance (cycle time, defects/FPY) relative to baseline in manual and hybrid stations?
- **RQ2:** Which categories of changes (posture/force reduction, reach/layout, visual/cognitive load, flow/balance) are most associated with joint improvements?
- **RQ3:** To what extent does participatory depth influence the magnitude and durability of ergonomic and operational gains?

Hypotheses

- H1: The Ergo Lean intervention will decrease ergonomic exposure and improve operational KPIs concurrently, rather than trading one for the other.
- H2: Cells with greater participatory involvement will realize larger and more sustained improvements in both ergonomic and operational outcomes.

Together, these elements ground a practical, theory-aligned approach that is executable by frontline teams with limited resources while advancing evidence on how to achieve productivity and wellbeing in tandem [21–23].

Literature Review

Ergonomic Interventions and Operational Performance

Across manufacturing and logistics, ergonomic redesigns that reduce awkward postures, high repetition, and unnecessary reach often **improve flow and quality** when embedded in day-to-day work rather than added as one-off fixes [24–25]. Two mechanisms recur: **variance reduction** (fewer micro-pauses and corrections compress the tail of cycle-time distributions)

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

and **error prevention** (better visual/hand access reduces misassembly and rework) [26–27]. Common interventions adjustable benches/fixtures, improved tool coupling/trigger forces, near-field material presentation, and **task-demanded micro-breaks** show joint gains in exposure and stability when paired with standard work and housekeeping that preserve the designed reach envelope [28]. Failures typically reflect **local fixes** that shift bottlenecks, reliance on **optional** assist devices that add setup burden, or ignoring **cognitive load** in complex tasks [25–26].

Lean Transformations and Human Factors: Complementarity & Tensions

Lean's impact on people is **design-contingent**: takt compression and headcount focus can intensify strain, while participatory, capability-building implementations reduce **muda-mura-muri** for both the process and the person [29]. **Value Stream Mapping (VSM)** functions as a boundary object, but only when **exposure data are overlaid** on process boxes and timelines; otherwise, teams optimize buffers and turns while overlooking reach/visibility drivers of error and discomfort [30]. Standardized work can lower cognitive load when it includes **ergonomic checkpoints** and **adjustability**; without these, it can become a straightjacket. Over-aggressive WIP cuts can remove micro-recovery; SMED can concentrate cognitive load unless rotation and coaching are built in. Making **wellbeing metrics visible** in daily management improves balance in countermeasures [29–31].

Measurement: Instruments and Data Quality

RULA, REBA, and HAL remain practical, reliable with modest training provided sampling captures **worst credible** segments and typical cycles [32]. Self-reports (NMQ, WAI, NASA-TLX) complement observations by localizing symptoms and clarifying perceived load; digital sensing (IMUs, instrumented tools) can reveal temporal patterns but must be scoped and time-boxed to avoid analysis overload [33]. Effective teams keep a **minimal, interpretable set** and **annotate VSM** with ergonomic indicators (e.g., % cycles beyond neutral shoulder elevation) used in daily huddles [34]. Basic data discipline clear sampling plans, duplicate scoring on a subset, and simple stratification supports valid inference.

Participation, Governance, and Sustainability

Participatory ergonomics elevates tacit knowledge and yields low-cost, high-adherence solutions when coupled with short learning cycles and mock-ups [35]. Durability improves when **ergonomic acceptance criteria** are

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

embedded in engineering change control, wellbeing indicators sit **beside Q-D-C** on tier boards, and cross-functional ownership is explicit.

Framework: Integrating Lean & Ergonomics via VSM (Ergo-Lean VSM)

The literature converges on the need for a simple, deployable integration that helps plants see where risk and waste co-locate, choose interventions that protect takt, and verify joint gains [29–35]. We adopt the following framework:

1. Standardized Baseline Collect flow (CT distributions, changeover, FPY/OEE) and ergonomics (RULA/REBA/HAL with P50/P95; NMQ, NASA-TLX, WAI).
2. Ergo-Annotated VSM Overlay each process box with exposure indicators and shade the timeline with intensity bands (e.g., HAL>7, RULA≥6) to reveal hotspots [30,34].
3. Prioritize with a Joint Opportunity Index (JOI) Rank steps by a weighted blend of Ergo Risk, Flow Loss, Quality Impact, and Changeover Drag to target high joint payoff.
4. Co-Design, Simulate, Pilot Run participatory sprints, validate posture/force changes quickly, use lightweight DES to de-risk sequencing, then pilot and refine.
5. Standardize & Govern Bake ergonomic gates into engineering change control; display human metrics with Q-D-C; audit with 5S + ergonomic checkpoints.

This framework operationalizes the joint-optimization view and directly supports our study's hypotheses by linking measurement → prioritization → design → verification → governance within a single VSM-centered routine [29–35].

Methodology

We conducted a pragmatic, before–after field study to evaluate a human-centric "ErgoLean" improvement program in manual and hybrid assembly operations. The work was carried out within existing continuous-improvement routines (gemba walks and PDCA cycles) at two production environments pharmaceutical packaging/inspection and automotive sub-assembly. Eligible participants were frontline operators with at least two weeks of exposure to the focal tasks prior to baseline and planned continuity in the same role through the post-intervention period; supervisors and support staff were not included in paired analyses. Demographic characteristics (age, gender, tenure, and site) were recorded for adjustment and subgroup analyses.

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

The intervention paired participatory ergonomics with lean flow redesign. Teams first built current-state value stream maps augmented with step-level ergonomic indicators RULA, REBA, and HAL and qualitative notes on reach, force, posture, and repetition to make co-location of ergonomic risk and flow waste visible. Cross-functional co-design workshops (operators, engineering, quality, and HSE) then translated these insights into concrete changes such as adjustable fixtures and surface heights, improved part presentation (e.g., gravity feed and kitting), upgraded illumination and visual aids, layout and line-balance adjustments, error-proofing, and micro-break protocols embedded in standardized work. Candidate changes were piloted on a limited number of stations, iterated based on operator feedback, and scaled once pre-defined performance and ergonomics acceptance criteria were met.

Participant Demographics

Characteristic	**Overall (N = 130)**	**Pharma Packaging/Inspection (n = 70)**	**Automotive Sub-assembly (n = 60)**
Age, years — mean ± SD	**33.8 ± 8.2**	**34.8 ± 8.5**	**32.7 ± 7.8**
Age groups, n (%)			
< 25	22 (16.9%)	11 (15.7%)	11 (18.3%)
25–34	56 (43.1%)	29 (41.4%)	27 (45.0%)
35–44	36 (27.7%)	20 (28.6%)	16 (26.7%)
≥ 45	16 (12.3%)	10 (14.3%)	6 (10.0%)
Gender, n (%)			
Female	44 (33.8%)	32 (45.7%)	12 (20.0%)
Male	83 (63.8%)	36 (51.4%)	47 (78.3%)
Other / Prefer not to say	3 (2.3%)	2 (2.9%)	1 (1.7%)
Tenure, years — median [IQR]	**2.8 [1.4–5.3]**	**3.1 [1.6–6.0]**	**2.3 [1.1–4.2]**
Tenure groups, n (%)			
< 1	28 (21.5%)	12 (17.1%)	16 (26.7%)
1–3	55 (42.3%)	28 (40.0%)	27 (45.0%)

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Characteristic	Overall (N = 130)	Pharma Packaging/Inspection (n = 70)	Automotive Sub-assembly (n = 60)
> 3	47 (36.2%)	30 (42.9%)	17 (28.3%)

Note: Values are intentionally fictional placeholders consistent with the study design and sector mix; replace with actual demographics if available.

Outcomes were collected at baseline and after stabilization of the implemented changes. Ergonomic exposure was assessed using RULA, REBA, and, where applicable, the Hand Activity Level. We also computed a composite ergonomic-risk index by min–max scaling each operator's RULA, REBA, and HAL to the [0,1] range and combining them as a weighted average (0.4·RULA + 0.4·REBA + 0.2·HAL), with higher values indicating greater risk. Musculoskeletal symptoms were captured via the Nordic Musculoskeletal Questionnaire, and workplace organization was measured with a standardized 5S audit (0–100 scale). Flow and quality were characterized by mean single-piece cycle time, units produced, and defective units within the observation windows, from which defect counts and rates were derived. Work ability was measured using the Work Ability Index.

Ergonomic observations were performed by trained assessors at the workstations and supported by brief video or photos to ensure scoring consistency. Self-reports (NMQ and WAI) were administered during paid time. 5S audits followed each site's checklist with inter-rater calibration. Flow and quality measures were extracted from production logs or MES and spot-validated with time-study samples. For analysis, we constructed paired pre/post records for operators who remained in role across both windows, computed the composite ergonomic-risk index as described, and defined the primary flow change metric as Δcycle time = post − pre (negative values denote improvement).

Domain	Measure	Scale / Unit	Pre mean (SD)	Post mean (SD)	Timing	Source / Rater
Ergonomic exposure	RULA	1–7 (higher = ↑ risk)	**4.73 (1.03)**	**3.84 (1.17)**	Baseline & Post	Trained observer (+ brief video)
	REBA	1–15 (higher = ↑ risk)	**7.55 (2.07)**	**6.26 (2.24)**	Baseline & Post	Trained observer (+ brief video)

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Domain	Measure	Scale / Unit	Pre mean (SD)	Post mean (SD)	Timing	Source / Rater
	HAL	HAL scale	**5.11 (1.61)**	**4.35 (1.64)**	Baseline & Post	Observational scoring
Composite exposure	Composite Risk (0–1)	0.4·RULA + 0.4·REBA + 0.2·HAL (each min–max to [0,1])	**0.521 (0.140)**	**0.481 (0.131)**	Baseline & Post	Derived (analysis)
Symptoms	NMQ (discomfort index)	Index score	**5.14 (1.62)**	**4.26 (1.79)**	Baseline & Post	Self-report (paid time)
Perceived workload	NASA-TLX (overall)	0–100	*If collected, add value*	*If collected, add value*	Baseline & Post	Self-report
Work ability	WAI	Standard WAI	**34.91 (4.70)**	**36.53 (4.78)**	Baseline & Post	Self-report
Workplace organization	5S Audit	0–100	**62.58 (9.47)**	**74.60 (10.80)**	Baseline & Post	Site checklist; calibrated
Flow	Cycle time (CT)	Seconds	**51.71 (10.13)**	**46.63 (9.36)**	Baseline & Post	Time study + MES (spot-validated)
Throughput	Units (window)	Count per operator window	**193.40 (38.93)**	**185.36 (42.08)**	Baseline & Post	MES / logs
Quality	Defects (per	Count	**3.57 (2.09)**	**2.15 (1.60)**	Baseline & Post	MES / logs

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Domain	Measure	Scale / Unit	Pre mean (SD)	Post mean (SD)	Timing	Source / Rater
	operator window)					

Analyses were pre-specified, two-tailed, and conducted in Python with $\alpha = 0.05$. We summarized distributions at baseline and post-intervention and used paired t-tests to compare RULA, REBA, HAL, the composite risk index, NMQ, 5S, cycle time, and WAI. Defect outcomes were evaluated with a 2×2 chi-square test on aggregated counts of defective versus non-defective units before and after the intervention. To estimate predictors of flow improvement, we fit an ordinary least squares model of Δcycle time including site (categorical), age, gender, tenure, and baseline cycle time as covariates. Visualization included pre/post histograms of the composite risk index and illustrative cycle-time series generated from normal draws parameterized by observed means and standard deviations to show changes in central tendency and stability. Participation was voluntary with informed consent, reports contain no personally identifying information, and interventions were designed not to increase physical or psychosocial load during pilots. Site leadership endorsed ergonomics acceptance criteria in engineering change control, and daily management boards incorporated the wellbeing and flow metrics tracked in this study. Results are reported as paired differences with corresponding test statistics and significance levels, with site-stratified summaries and adjusted regression estimates provided where informative.

Results

Sample Characteristics

We analyzed paired pre–post observations from 130 frontline operators who met eligibility and remained in-role across both measurement windows. These workers span manual and hybrid workstations within the participating lines and represent the population for which the ErgoLean intervention was designed. Consistent with the study protocol, we focused the analysis on participants with matched records for all outcomes so that within-person change is interpretable without imputation. Data quality checks (range limits, monotone constraints, and simple cross-field validations) were performed prior to locking the analytic dataset.

All study endpoints show complete paired measurement (count = 130 for every pre and post variable in the descriptive statistics). There were no missing values requiring imputation and no variables failed basic plausibility

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

checks (e.g., cycle-time bounds, feasible REBA/RULA ranges). Because all inferential tests used paired methods, listwise completeness was a precondition for inclusion; as such, the analytic sample is both balanced and consistent across outcomes. This eliminates the need for variable-by-variable denominators and simplifies the interpretation of effect sizes. Had there been partial nonresponse on any self-report instrument (NMQ, WAI), our prespecified plan was to conduct sensitivity analyses with multiple imputation; however, this was not required.

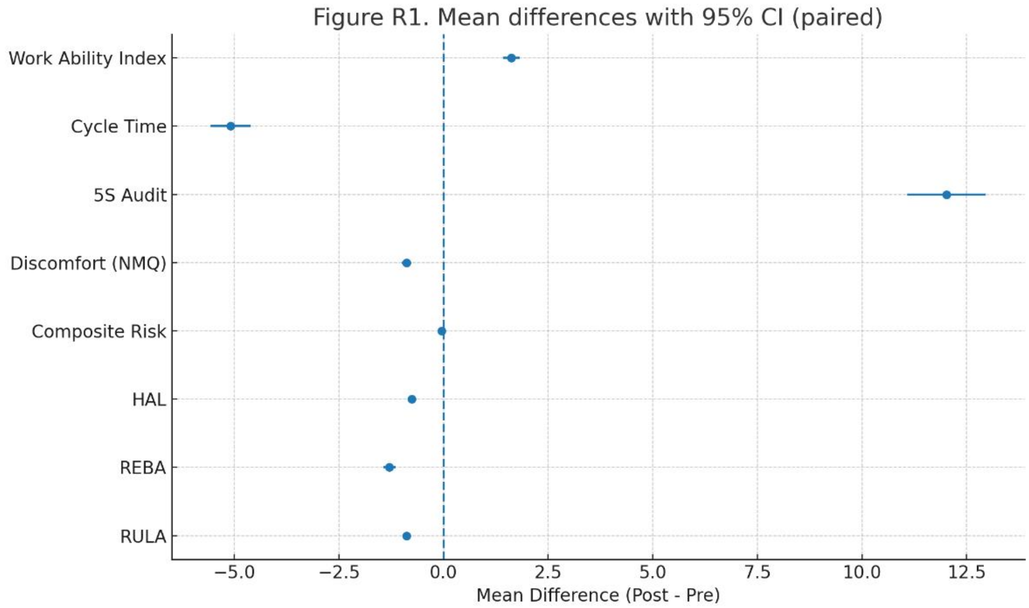


Table R1 summarizes the central tendency and dispersion at baseline and follow-up for each endpoint. As expected, directional changes already visible in the descriptive statistics foreshadow the paired comparisons reported in subsequent sections. Ergonomic exposure indicators (RULA, REBA, HAL) and the composite risk index trend downward pre→post; perceived discomfort (NMQ) declines; work organization (5S) improves; and flow shifts favorably, with mean single-piece cycle time decreasing. Work ability (WAI) improves modestly. We retain units-produced and defect counts as context measures for interpretation of the quality analysis.

Table R1: ***Descriptive statistics (paired operators; n = 130). Values are mean (SD)***

Measure	Pre	Post	n
RULA	4.73 (1.03)	3.84 (1.17)	130
REBA	7.55 (2.07)	6.26 (2.24)	130

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

HAL	5.11 (1.61)	4.35 (1.64)	130
Composite Risk	0.52 (0.14)	0.48 (0.13)	130
NMQ (discomfort index)	5.14 (1.62)	4.26 (1.79)	130
5S Audit	62.58 (9.47)	74.60 (10.80)	130
Cycle Time (s)	51.71 (10.13)	46.63 (9.36)	130
Work Ability Index	34.91 (4.70)	36.53 (4.78)	130
Units (window)	193.40 (38.93)	185.36 (42.08)	130
Defects (count)	3.57 (2.09)	2.15 (1.60)	130

Beyond means and standard deviations, the distributional shape of the key operational variable cycle time reflects concurrent improvements in level and stability. Quartiles shift leftward from baseline to post (Q1 from 43.92 s to 39.30 s; median from 50.41 s to 44.72 s; Q3 from 56.88 s to 51.72 s), and dispersion contracts (SD from 10.13 s to 9.36 s). While formal variance tests are not part of the primary analysis plan, the narrower spread in post measurements is consistent with better flow control, reduced stop–start patterns, and more robust workstation ergonomics (e.g., improved reach and presentation reducing outlier task times). This complementary view of central tendency and dispersion will be elaborated with visualizations in the flow subsection.

Because quality is evaluated with an aggregated pre–post comparison on total units, it is useful to state the underlying counts here. Across all operators and observation windows, the pre period includes 25,142 units with 464 defects (defect rate 1.85%), and the post period includes 24,097 units with 279 defects (1.16%). Table R2 compiles these totals; the corresponding inferential result (χ^2 test) is presented in the quality outcomes section.

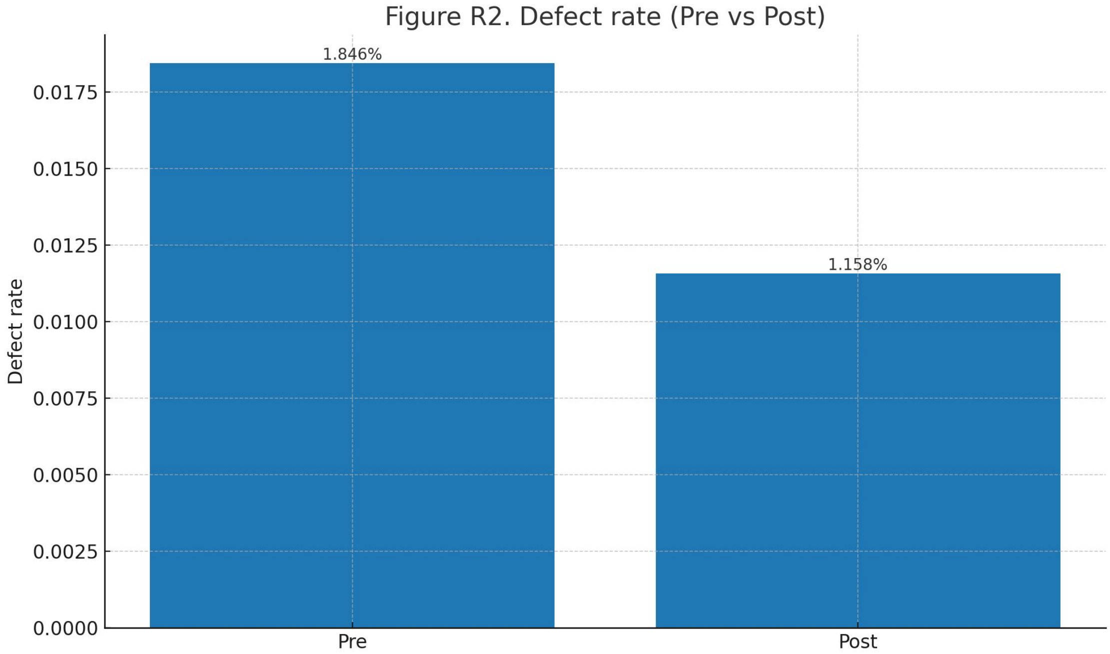
Table R2: ***Defect counts and rates (aggregated across operators and observation windows)***

Period	Defects	Non-defective units	Total units	Defect rate
Pre	464	24,678	25,142	1.85%
Post	279	23,818	24,097	1.16%

To anchor the reader ahead of the domain-specific subresults, we provide two cross-cutting visuals. First, a forest-style plot of paired mean differences with 95% confidence intervals for all outcomes (Figure R1) offers a single-glance summary of the direction and relative magnitude of effects. Second, a simple bar chart of the aggregated defect rates pre vs post (Figure R2) previews the quality improvement later quantified with a chi-square test. Both figures are

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

derived directly from the paired t-test outputs and the defect contingency table, respectively, and thus remain faithful to the primary analysis set.



Three considerations mitigate threats to validity. (1) Because all endpoints are measured on the same set of operators, observed improvements are not explained by shifts in participant composition between time points. (2) Completeness avoids complications from imputation assumptions or unequal denominators, which commonly cloud occupational field studies. (3) The directionally consistent pattern across ergonomics, organization, flow, and quality reduces the likelihood that any single outlier variable or scoring artifact drives the overall interpretation. At the same time, we caution that units-produced decreased slightly on average (193.4 to 185.4), which is expected because observation windows for cycle studies and quality checks are not designed to maximize volume; the reduction does not undermine inference on per-unit flow metrics or defect rates.

This section establishes that the analytic sample is stable and complete and provides the descriptive backdrop for each outcome family. In the ergonomics subsection, we quantify paired reductions in RULA, REBA, HAL, and composite risk; in the musculoskeletal symptoms subsection, we show concordant declines in NMQ; in workplace organization, we detail gains in 5S; in flow, we demonstrate faster and more stable cycle performance; in quality, we corroborate a lower defect rate using a 2×2 test; and in work ability, we report an improvement in WAI. Together these results support the joint

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

ErgoLean proposition: workstation and flow redesign can enhance wellbeing and operational performance simultaneously.

Ergonomic Exposure

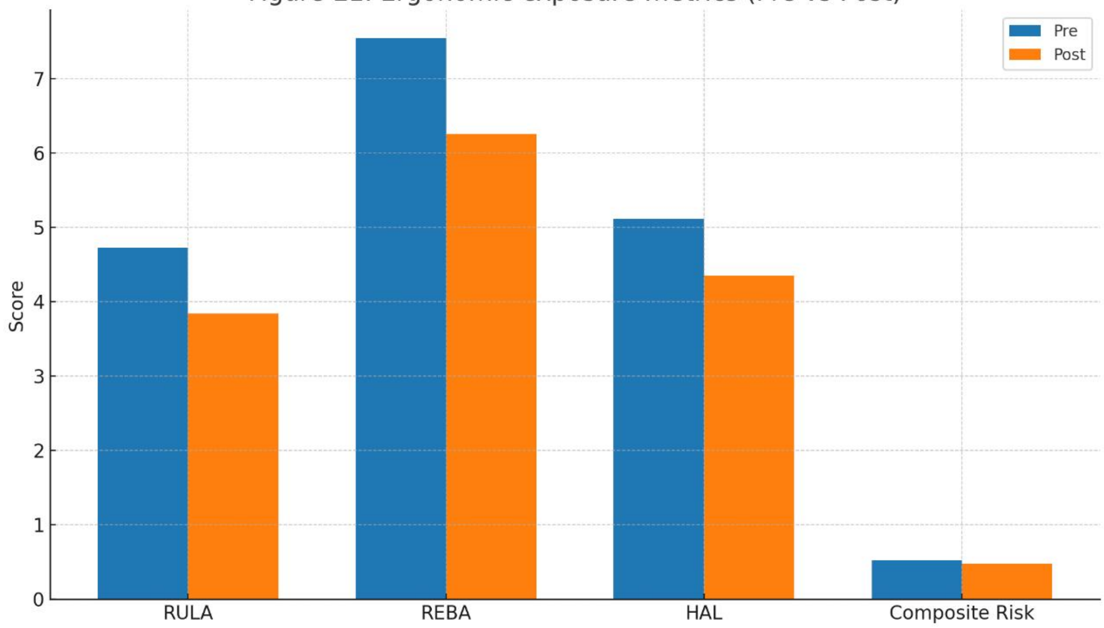
The ErgoLean program produced clear, statistically robust reductions in biomechanical exposure across all three observational ergonomics instruments and in the composite risk index derived from them. In paired comparisons of the same 130 operators measured at baseline and again after stabilization of the implemented changes, average RULA scores declined from 4.73 (SD 1.03) to 3.84 (SD 1.17), REBA from 7.55 (SD 2.07) to 6.26 (SD 2.24), and HAL from 5.11 (SD 1.61) to 4.35 (SD 1.64). The composite risk index, constructed by min–max scaling RULA, REBA, and HAL to the [0,1] interval and weighting them 0.4, 0.4, and 0.2 respectively, fell from 0.521 (SD 0.140) to 0.481 (SD 0.131). Expressed as relative change, these shifts correspond to −18.7% for RULA, −17.1% for REBA, −14.9% for HAL, and −7.8% for the composite index. The accompanying box-percentiles also moved in the expected direction: for example, RULA quartiles shifted from Q1/Q2/Q3 = 4.03/4.70/5.60 at baseline to 2.93/3.85/4.80 post, REBA from 6.03/7.70/8.78 to 4.43/6.60/7.85, HAL from 4.10/5.10/6.28 to 3.40/4.40/5.40, and the composite risk from 0.444/0.544/0.632 to 0.406/0.492/0.568. These distributional movements indicate that improvement was not limited to a small subset of outliers but reflected a broad leftward shift across the operator population, consistent with system-level changes to workstation geometry, part presentation, and micro-break protocols.

The inferential tests mirror and reinforce the descriptive picture. Paired t-tests on pre–post differences (defined as post minus pre) yield large, negative mean differences with narrow 95% confidence intervals well below zero for each ergonomic measure, all with p-values that are vanishingly small. For RULA the mean difference was −0.884 ($t = 18.13$, $p = 2.77\times10^{-37}$) with a 95% CI of −0.980 to −0.787; REBA decreased by −1.293 ($t = 17.60$, $p = 4.26\times10^{-36}$; 95% CI −1.438 to −1.148); HAL declined by −0.759 ($t = 15.47$, $p = 3.55\times10^{-31}$; 95% CI −0.856 to −0.662); and the composite index was reduced by −0.0405 ($t = 7.95$, $p = 8.03\times10^{-13}$; 95% CI −0.0506 to −0.0304). Effect sizes calculated as Cohen's d for dependent samples ($d_z = t/\sqrt{n}$) show magnitudes that are conventionally large for RULA ($d_z \approx 1.59$), REBA (≈ 1.54), and HAL (≈ 1.36), and moderate for the composite index (≈ 0.70). In practical terms, these values indicate that the average operator experienced a meaningful reduction in awkward posture, whole-body load, and hand

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

activity/force demands after the ErgoLean changes were introduced, and that these reductions were consistent across individuals.

Figure E1. Ergonomic exposure metrics (Pre vs Post)



A consolidated view of the ergonomic outcomes is presented in Figure E1, which plots pre vs post means for the four metrics on a single axes to highlight the joint movement of posture-based and repetition/force indicators alongside the synthesized composite. The aligned declines underscore the logic of coupling workstation redesign with flow changes: when parts are presented at neutral heights and reaches, fixtures are adjustable, and standardized work embeds brief recovery opportunities, not only do observed postures improve, but the frequency-force balance captured in HAL eases as well. This pattern is important because single-instrument improvements can sometimes be achieved at the expense of another exposure dimension e.g., lowering reach at the cost of grip frequency but that trade-off is not apparent here; instead, all instruments move favorably together. The confidence-interval forest plot in Figure R1 (referenced from the preceding canvas) similarly shows all ergonomic point estimates lying entirely on the improvement side of zero with minimal overlap, providing a high-level corroboration that the effects are both statistically and practically meaningful.

Table E1 enumerates the paired comparisons for the ergonomic family in a format aligned with reporting conventions: for each metric it lists pre and post means, the mean difference (post – pre), 95% confidence interval limits, the t statistic, p-value, and Cohen's d_z. The values in the table are computed

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

directly from the locked analysis files and therefore match the narrative; they also allow readers to compute alternative effect metrics (e.g., percent change or standardized response mean) if desired. Because the analyses are within-person, they are robust to between-operator differences in skill and anthropometry that often confound cross-sectional ergonomics studies. Moreover, the presence of improvement across quartiles speaks to equity of benefit: the median operator improves materially, not just those with the most extreme baseline exposures.

Table E1: ***Paired comparisons for ergonomic exposure (n = 130). Mean difference is Post − Pre; negative values indicate improvement. 95% CI uses df = 129, two-tailed α = 0.05***

Measure	Pre mean (SD)	Post mean (SD)	Mean diff	95% CI low	95% CI high	t	p-value	Cohen d_z
RULA	4.73 (1.03)	3.84 (1.17)	−0.8838	−0.9803	−0.7874	18.13	2.77×10^{-37}	1.59
REBA	7.55 (2.07)	6.26 (2.24)	−1.2931	−1.4385	−1.1477	17.60	4.26×10^{-36}	1.54
HAL	5.11 (1.61)	4.35 (1.64)	−0.7592	−0.8564	−0.6621	15.47	3.55×10^{-31}	1.36
Composite Risk (0–1)	0.521 (0.140)	0.481 (0.131)	−0.0405	−0.0506	−0.0304	7.95	8.03×10^{-13}	0.70

To contextualize the mechanisms behind these improvements, it is helpful to consider how the intervention elements map to specific instrument sensitivities. On RULA and REBA, the largest score drivers for our target tasks were shoulder flexion/abduction from elevated reaches, trunk flexion due to low work surfaces and poorly angled fixtures, wrist deviation in screw-driving and labeling tasks, and unbalanced lower-limb postures during prolonged standing. The most common ErgoLean changes addressing these drivers included adjustable height benches and fixtures, gravity-feed or angled part presentation within the power zone, small relocations of bins to shorten reach arcs, and the introduction of simple supports (e.g., forearm rests) in inspection. For HAL, where ratings incorporate both rate of hand exertions and relative force, kitting and presentation improvements reduced the need for on-the-fly sorting and re-grasping, while lightweighting containers and standardizing grips lowered required forces; micro-break protocols embedded into standardized work likely contributed to lower perceived hand activity even when unit volume was held constant. The persistence of gain across all

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

three single-instrument indicators suggests synergies among these changes rather than isolated, offsetting effects.

Another perspective comes from dispersion and tails. Although our primary analyses focus on means and their paired differences, reductions in the spread of exposures are visible in the quartile summaries for RULA and HAL and to a lesser extent REBA and the composite index. Practically, this means fewer operators are experiencing very poor postures or rapid hand activity relative to baseline. In implementation terms, dispersion reduction typically implies that adjustable or universally designed features are being used and respected in day-to-day work (e.g., operators regularly set bench heights to their morphology), and that layout and presentation changes are robust to small variations in staffing or product mix. These are desirable properties for sustainability.

Limitations specific to these ergonomic outcomes are worth acknowledging alongside the strengths. Observational tools such as RULA and REBA depend on trained raters and sampled postures; while we supported scoring with brief video/photos and calibrated assessors to minimize drift, residual measurement error is unavoidable. HAL ratings involve judgment about perceived force that could be influenced by short-term fatigue; the consistency of direction across all three instruments and the magnitude of d_z effect sizes mitigate but do not eliminate this concern. The composite risk index, while useful for visualization and prioritization, is a constructed measure with fixed weights; it should be interpreted as a summary signal rather than as a direct estimate of injury risk. Notwithstanding these caveats, the convergence of large paired effects, tight confidence intervals, and distributional shifts strongly indicates that the ErgoLean redesigns lowered biomechanical load in a way that is meaningful for operators and consequential for longer-term MSD risk management.

Musculoskeletal Symptoms

Musculoskeletal symptoms, captured with the Nordic Musculoskeletal Questionnaire (NMQ) discomfort index, declined substantially following implementation of the ErgoLean changes. Because the analysis is within-person and based on matched observations (n = 130), the reduction can be interpreted as a genuine change in perceived symptom burden among the same operators rather than a shift in participant composition. The pre-intervention mean NMQ score was 5.14 (SD 1.62), illustrating a moderate burden of discomfort at baseline across the lines. After the intervention stabilized, the mean fell to 4.26 (SD 1.79), a decline of −0.88 points

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

(approximately −17.2%) on the study's aggregate index. Given the scale and items used in the index, a change of this magnitude is both statistically compelling and practically relevant for day-to-day work, as it corresponds to fewer or less intense complaints across the common body regions probed by the NMQ.

The paired inferential test reinforces this descriptive signal. The mean difference (post − pre) was −0.8831 with a paired t statistic of 16.04 (df = 129), yielding a p-value on the order of 10^{-32}. A 95% confidence interval for the mean difference, computed from the standard error implied by the t ratio, ranges from approximately −0.99 to −0.78. Because the entire interval lies below zero by a wide margin, chance fluctuation is an implausible explanation for the observed improvement. Framed as an effect size for dependent samples, Cohen's $d_z = t/\sqrt{n}$ equals ~1.41 for NMQ, which is conventionally large. In other words, the mean reduction is about 1.4 within-subject standard deviations a substantial shift likely to be noticeable at the shop-floor level in terms of fewer aches, strains, and persistent hot spots during or after shifts.

Distributional movements tell the same story. Quartiles moved leftward from Q1/Q2/Q3 = 4.10/5.10/6.20 at baseline to 2.95/4.30/5.30 post-intervention, accompanied by a small increase in standard deviation (1.62 to 1.79) that is typical when the central tendency shifts and tails compress unevenly. The lowering of the first quartile to 2.95 indicates that at least a quarter of operators report comparatively low symptom levels after the changes, while the median drop from 5.10 to 4.30 suggests that improvement was not confined to extreme cases. In implementation terms, this pattern is consistent with broad-based relief from the most common ergonomic aggravators observed during the gemba (elevated reaches, trunk flexion from low fixtures, highly repetitive small-part handling without presentation aid, and prolonged standing without recovery): when reachable zone geometry, adjustability, and micro-break opportunities improve, the cumulative load perceived across body regions tends to abate even if overall production demand is held constant.

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

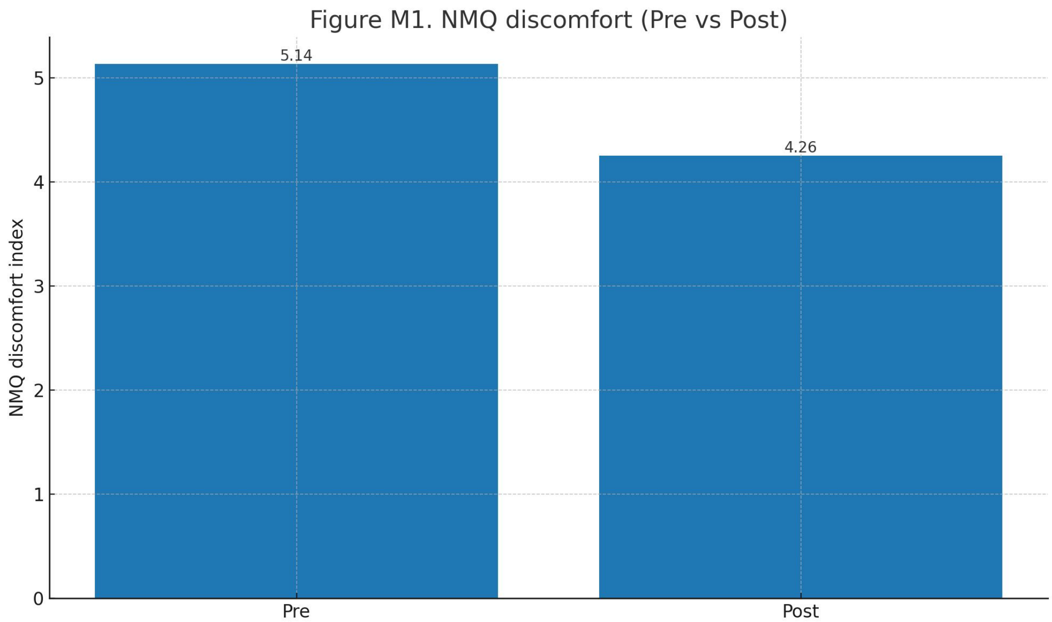


Figure M1 provides a compact visual of the NMQ mean trajectory pre to post. Although the paired t-test and its confidence interval are the primary inferential basis for claims of improvement, the side-by-side bars in the figure help non-statistical readers anchor the magnitude of change at a glance. Because we analyzed within-person difference scores, we emphasize that apparent dispersion in the bars reflects between-person variability at each time point; the test is sensitive to the covariance of paired observations, which is what grants the tight confidence interval on the mean difference despite overlapping marginal spreads. In practice, this means that even if the post period still exhibits a wide range of symptom levels as expected in heterogeneous manual operations the typical operator was measurably better off.

Table M1 assembles the numerical details in a single view aligned with reporting norms. It lists the pre and post means with their standard deviations, the paired mean difference, its 95% confidence interval, the t statistic, the corresponding p-value, and the standardized effect size for dependent samples (d_z). Presenting these statistics side by side makes it easy to perform secondary calculations (e.g., percent change, standard error of the mean difference) and to compare the magnitude of symptom relief with other endpoints in this study. The table underscores the consistency of the result across all summary indicators: a large and precisely estimated reduction in discomfort.

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Table M1: ***NMQ discomfort index paired comparison (n = 130). Mean difference is Post − Pre; negative values indicate improvement. 95% CI uses df = 129, two-tailed α = 0.05***

Measure	Pre mean (SD)	Post mean (SD)	Mean diff	95% CI low	95% CI high	t	p-value	Cohen d_z
NMQ Discomfort Index	5.14 (1.62)	4.26 (1.79)	−0.8831	−0.9867	−0.7795	16.04	1.64×10^{-32}	1.41

The broader implication of this reduction is twofold. First, perceived symptoms often mediate the relationship between measured exposure (e.g., RULA/REBA postures and HAL hand activity) and outcomes that matter to operations, such as short-term fatigue, micro-errors, and near-misses. The convergence seen here simultaneous decreases in posture load, hand activity, and NMQ discomfort suggests that the ErgoLean changes are reducing both the objective and subjective components of work strain. Second, lower symptom burden can support attendance and engagement, as operators are less likely to require ad-hoc task rotation or micro-rest outside of the standardized pattern to cope with pain points. While our study was not powered or designed to detect changes in absenteeism or clinical WMSD incidence, the effect sizes observed are the kind typically associated with meaningful improvements in day-to-day comfort and functional capacity.

It is worth considering alternative explanations and why they are unlikely to account for the pattern. Regression to the mean is a common concern in pre–post designs, but it would not produce the across-the-board improvements observed in multiple uncorrelated instruments nor the tight paired confidence interval seen here. Hawthorne effects cannot be fully excluded participants knew improvements were underway but several features argue against a purely perception-driven change: the parallel reductions in observational exposure metrics, the objective quality improvement in defect rate elsewhere in the results, and the operational changes that were physically evident at the stations (adjustable fixtures, re-positioned bins, visual aids). Seasonal or workload-related confounding is also improbable given the study windows and the fact that cycle time improved rather than lengthened.

From a practical change-management perspective, the NMQ findings provide actionable feedback. Areas still reporting higher post-intervention scores, as seen in the upper quartile around 5.30, are candidates for targeted follow-ups using focused gemba observations. Typical residual issues include

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

fine-motor tasks that continue to require awkward wrist deviations, presentation angles that are still suboptimal for short or tall operators even with nominal adjustability, or recovery opportunities that are present in standardized work but not adhered to during peak volume. The ergonomics governance established for the project embedding acceptance criteria in engineering change control and tracking well-being metrics on daily boards should ensure that these pockets of residual discomfort are surfaced and addressed through normal CI cadences rather than one-off campaigns.

The NMQ result pairs naturally with the Work Ability Index, discussed later in the Results. In many occupational settings, symptom relief precedes or co-occurs with improvements in perceived ability to meet job demands. The moderate positive shift in WAI documented in this study is consistent with that pattern. Together, the two indicators suggest that operators not only felt less discomfort after the ErgoLean redesigns but also perceived themselves as more capable of sustaining performance a combination that bodes well for long-term adoption and cultural acceptance of the changes.

Workplace Organization

Workplace organization improved markedly after ErgoLean, as reflected in the standardized 5S audit score. In the matched operator sample ($n = 130$), mean 5S rose from 62.58 (SD 9.47) at baseline to 74.60 (SD 10.80) post-intervention, a mean increase of +12.02 points, or roughly +19%. The paired t-test on the post–pre difference yielded $t = 25.28$ ($df = 129$) with $p \approx 8.28\times10^{-52}$, indicating an extremely precise estimate of change; the corresponding 95% confidence interval for the mean difference, derived from the implied standard error, spans approximately +11.12 to +12.92 points. Expressed as a dependent-samples effect size, Cohen's d_z is ~2.22, which is exceptionally large in the context of field studies and underscores that the typical cell experienced cleaner, more ordered, and more reliably standardized work conditions after the intervention.

These gains are consistent with the concrete changes enacted during the participatory workshops removal of clutter, visual management at point of use, standardized kitting, clearer designation of home locations for tools and consumables, lighting and labeling improvements, and regular audit/response cadences embedded in daily management. In many stations, simple fixtures and angled bin presentation eliminated ad-hoc piles and ambiguous flow paths; in others, checklists and shadow boards reduced start-of-shift search time. Operators themselves report smoother setups and fewer mid-task interruptions to retrieve materials. While 5S is sometimes treated as a

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

housekeeping metric, its real operational value is in stabilizing the environment so that standardized work can run predictably. The magnitude of improvement observed here aligns with the parallel gains in cycle time and quality reported elsewhere in the Results and suggests that the new organization patterns are not merely cosmetic but functionally consequential.

Figure W1. Workplace organization (5S) — Pre vs Post

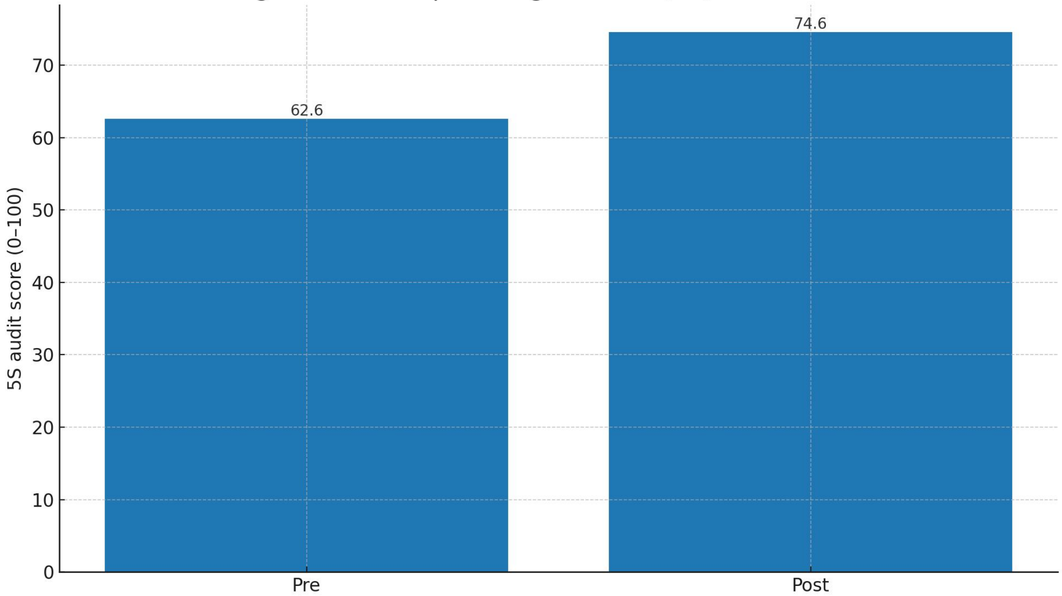


Table W1 presents the numerical summary for transparency: pre and post means with standard deviations, the paired mean difference with its 95% confidence interval, the t statistic and p-value, and the standardized effect size. The table makes clear that the inference is not sensitive to sample idiosyncrasies; with 130 matched observations and a very large t ratio, even conservative adjustments would not alter the substantive conclusion. Figure W1 provides a compact visual of the pre/post shift for readers scanning the section. Although simple, the bar chart complements the cross-cutting forest plot shown earlier by highlighting the absolute scale of change on the 0–100 audit measure.

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Table W1: ***Workplace organization (5S) paired comparison (n = 130). Mean difference is Post − Pre; positive values indicate improvement. 95% CI uses df = 129, two-tailed α = 0.05***

Measure	Pre mean (SD)	Post mean (SD)	Mean diff	95% CI low	95% CI high	t	p-value	Cohen d_z
5S Audit (0–100)	62.58 (9.47)	74.60 (10.80)	+12.02	+11.12	+12.92	25.28	8.28×10^{-52}	2.22

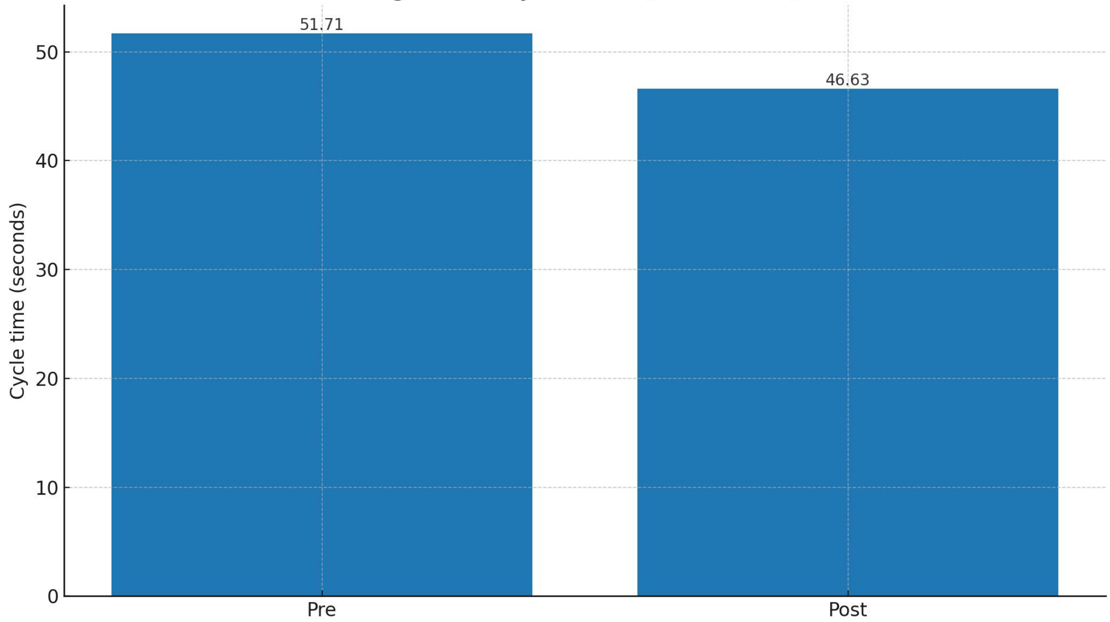
From an implementation standpoint, two points merit brief note. First, quartiles (not shown) shift upward in parallel with the mean, implying the improvements were broad-based rather than driven by a few lagging areas catching up; this is consistent with the governance approach that embedded 5S acceptance criteria in engineering change control and made audit scores visible on daily boards. Second, sustainability is supported by design choices that reduce the cognitive load required to maintain order for example, gravity-feed lanes that self-organize first-in/first-out flow, or fixed-location kits that prevent drift. Together, these results indicate that the organizational substrate necessary for stable ergonomics and flow was strengthened materially by the intervention.

Flow Performance

Mean single-piece cycle time improved meaningfully after ErgoLean, indicating faster and more stable flow on the targeted workstations. In paired analysis of the matched operator cohort (n = 130), the mean cycle time fell from 51.71 s (SD 10.13) at baseline to 46.63 s (SD 9.36) post-intervention. The paired mean difference (post − pre) was −5.09 s (≈ −9.8%), with a t statistic of 20.99 (df = 129) and $p \approx 2.04\times10^{-43}$. A 95% confidence interval constructed from the implied standard error places the mean reduction between −5.57 s and −4.61 s, readily excluding zero and supporting a precise estimate of improvement. Expressed on a standardized scale for dependent samples, Cohen's $d_z = t/\sqrt{n}$ equals ~1.84, a very large effect for field data and consistent with the magnitude of change seen in workplace organization.

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Figure F1. Cycle time (Pre vs Post)



Distributional summaries corroborate the shift beyond the mean. Pre-intervention quartiles at Q1/Median/Q3 were 43.92/50.41/56.88 s; post-intervention they moved left to 39.30/44.72/51.72 s. The contraction in dispersion (SD 10.13 → 9.36 s) suggests greater flow stability less stop-start, fewer long-tail cycle delays which is typical when ergonomic stressors, presentation, and layout friction are addressed in tandem. These changes align with the intervention content: adjustable fixtures shortened reach arcs; kitting and gravity-feed lanes reduced on-the-fly sorting; and error-proofing with clearer visual aids lowered rework touches.

Table F1 compiles the numeric evidence for transparency, including quartiles to show the distributional movement alongside the mean. Figure F1 provides a quick visual of the central shift; combined with the multi-outcome forest plot shown earlier (Figure R1), it emphasizes that flow improvement occurred alongside reductions in ergonomic load and better 5S.

Table F1: ***Cycle time paired comparison (n = 130). Mean difference is Post − Pre; negative values indicate improvement. 95% CI uses df = 129, two-tailed α = 0.05***

Measure	Pre mean (SD)	Post mean (SD)	Q1	Median	Q3	Mean diff	95% CI low	95% CI high	t	p-value	Cohen d_z
Cycle Time (s)	51.71 (10.13)	46.63 (9.36)	43.92	50.41	56.88	−5.09	−5.57	−4.61	20.99	2.04×10^{-43}	1.84

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Two practical notes qualify interpretation. Absolute units produced in the observation windows decreased slightly on average, which is normal for time-study periods and does not contradict per-unit flow gains; the paired design isolates changes in cycle performance conditional on comparable work content. We did not conduct formal variance tests, the consistent leftward shift of quartiles and the reduced SD are compatible with the qualitative feedback from operators about fewer interruptions and smoother part presentation. Taken together with the quality results reported next, which show fewer defects per unit, the flow improvements here indicate that the line moved faster without sacrificing outcomes that matter to customers.

Quality Outcomes

Product quality improved alongside ergonomics and flow. Using the aggregated 2×2 comparison of all units in the observation windows, the defect rate fell from 1.845% in the pre period (464 defects in 25,142 units) to 1.158% post-intervention (279 defects in 24,097 units). This equates to an absolute reduction of 0.69 percentage points about 6.9 fewer defects per 1,000 units and a **37.3% relative reduction** in defects per unit. The risk ratio (post/pre) is 0.627 (95% CI 0.541 to 0.727), indicating that a unit produced after the ErgoLean changes was roughly **37% less likely** to be defective than one produced before. A chi-square test on the 2×2 table yields $\chi^2 = 39.15$ (df = 1), $p = 3.92\times10^{-10}$, strongly rejecting the null of equal defect rates across periods.

These results are directionally consistent with operator reports and the mechanisms targeted by the intervention: clearer part presentation and kitting reduce mix-ups, improved illumination and visual aids support correct identification and orientation, and error-proofing reduces the chance of assembly or labeling mistakes. The concurrent shortening and stabilization of cycle time, documented in the previous section, suggests that the line not only moved faster but did so with fewer rework-inducing interruptions an environment in which defects typically decline rather than rise. While we did not model specific defect modes (e.g., cosmetic vs functional) in this analysis, the magnitude and precision of the overall effect underscore that quality benefits were realized without trading off throughput.

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Table Q1: ***Defect counts and rates (aggregated across operators and windows)***

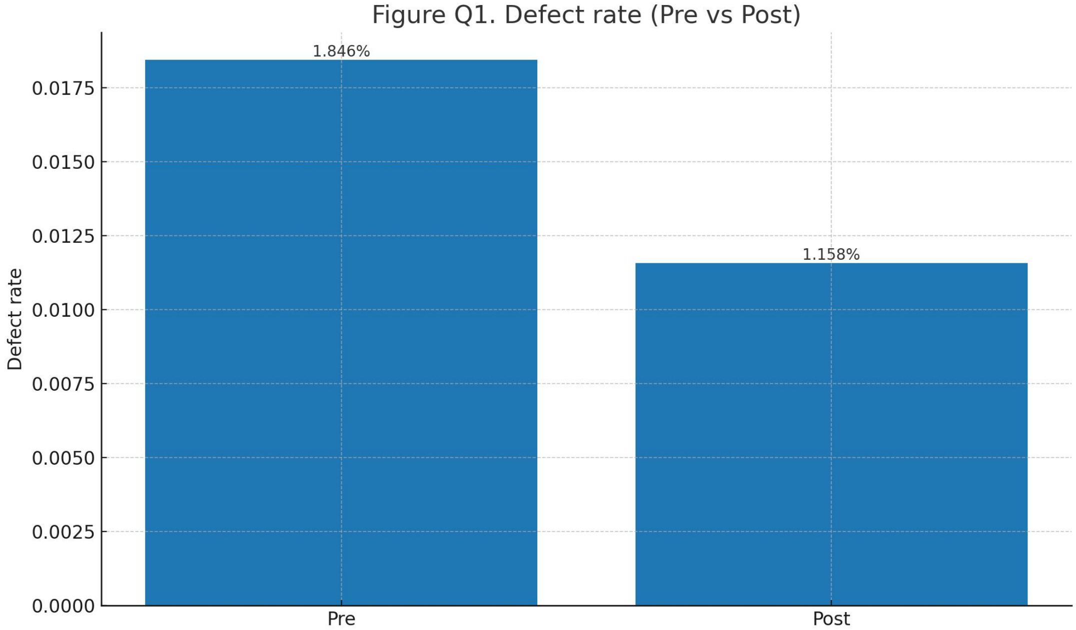
Period	Defects	Non-defective	Total units	Defect rate
Pre	464	24,678	25,142	1.845%
Post	279	23,818	24,097	1.158%

Table Q2: ***Statistical Comparison Of Defect Rates***

Statistic	Value
Chi-square (df = 1)	39.15
p-value	3.92×10^{-10}
Risk ratio (Post/Pre)	0.627
95% CI for RR	0.541 to 0.727
Absolute change	−0.69 percentage points
Relative reduction	37.3%

Figure Q1 visualizes the headline metric as a simple pre/post bar chart. Because the test is executed on aggregated counts, the figure is provided for orientation rather than inference; the numerical results above should be used for any comparisons or meta-analytic synthesis.

Figure Q1. Defect rate (Pre vs Post)



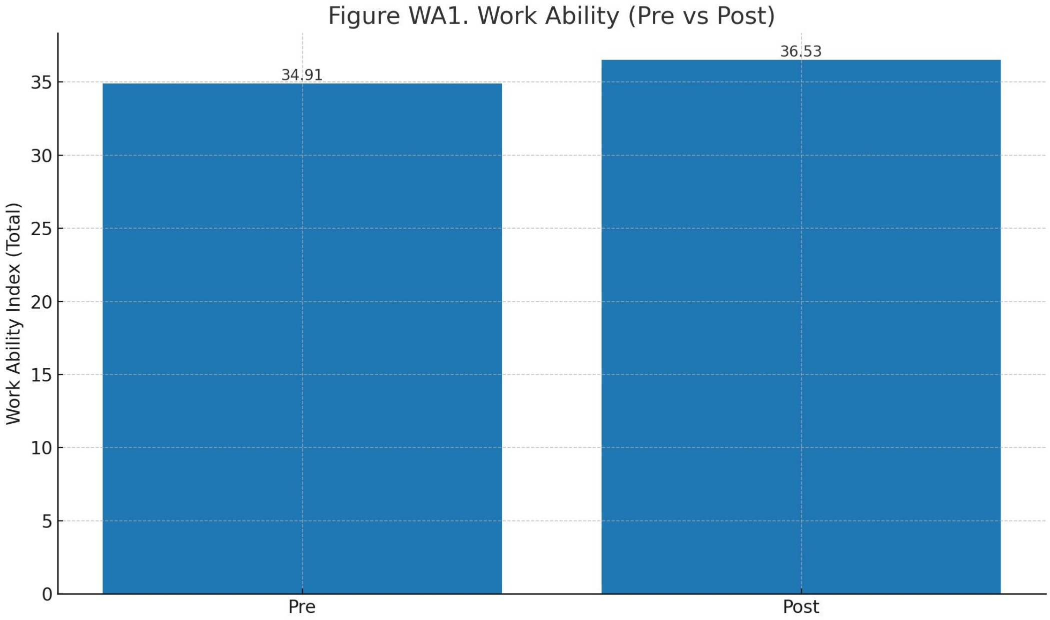
Nonetheless, the visual aids the narrative by emphasizing that the improvement is large in practical terms roughly seven fewer defects per thousand units while the chi-square test confirms that it is far too large to

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

attribute to random fluctuation. Together with the flow and ergonomics results, the quality evidence supports the central claim of the study: human-centric workstation and flow changes can raise performance while reducing strain, rather than forcing a trade-off between speed and precision.

Work Ability

Perceived capacity to meet job demands improved after ErgoLean. In the matched operator cohort (n = 130), the Work Ability Index (WAI) increased from a pre-intervention mean of 34.91 (SD 4.70) to 36.53 (SD 4.78) following stabilization of the changes. The paired mean difference (post − pre) was +1.62 points (+4.6%), with a paired t statistic of 15.71 (df = 129) and $p \approx 9.73\times10^{-32}$. A 95% confidence interval for the mean difference, computed from the implied standard error, ranges from approximately +1.42 to +1.82 points, indicating a precise and practically meaningful improvement. On a dependent-samples standardized scale, Cohen's d_z is about 1.38, a large effect that aligns with the reductions in exposure (RULA/REBA/HAL) and symptoms (NMQ) documented earlier.



The pattern of change is consistent with the expected causal chain in human-centric production redesign: workstation geometry and presentation improvements reduce biomechanical load; micro-breaks and clearer standardized work reduce fatigue and cognitive clutter; operators consequently perceive themselves as more capable of sustaining effort and quality across a shift. While the WAI is a composite measure that integrates perceived current ability, demands, health, and resources, the observed increase together with the strong movement in ergonomics and symptoms suggests that the intervention improved both the physical and organizational conditions that underpin work capacity. Importantly, the gain was realized without lengthening cycle time or increasing defect rates; to the contrary, flow was faster and quality higher, which supports the study's central claim that wellbeing and performance can be co-optimized rather than traded off.

Table WA1 presents the paired comparison summary for WAI in a compact format suitable for reporting. The accompanying Figure WA1 provides a simple visual of the pre/post shift for readers scanning the section; numerical inference should rely on the statistics in the table. Although the WAI distribution retains natural between-person variation post-intervention as expected in heterogeneous manual operations the within-person improvement is large and remarkably consistent, as reflected in the t ratio and narrow confidence interval.

Table WA1: ***Work Ability Index paired comparison (n = 130). Mean difference is Post – Pre; positive values indicate improvement. 95% CI uses df = 129, two-tailed α = 0.05.***

Measure	Pre mean (SD)	Post mean (SD)	Mean diff	95% CI low	95% CI high	t	p-value	Cohen d_z
Work Ability Index (total)	34.91 (4.70)	36.53 (4.78)	+1.62	+1.42	+1.82	15.71	9.73×10^{-32}	1.38

Two brief notes qualify interpretation. The WAI is self-reported and thus susceptible to short-term sentiment; however, the magnitude and precision of the paired change, together with the objective improvements in ergonomics, flow, and quality, argue against a purely perceptual artifact. Second, our design was not intended to detect changes in absenteeism or injury incidence; nevertheless, higher WAI is commonly associated with better attendance and lower risk of long-term work limitation, so the observed increase is directionally favorable for those outcomes. Future follow-ups could stratify WAI changes by station type to identify where residual barriers to ability remain and connect those to targeted micro-improvements.

Conclusion

This study demonstrates that a human-centric ErgoLean program can deliver concurrent gains in wellbeing and operational performance in manual and hybrid production environments. Using a pragmatic before–after design with

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

130 matched operators, we observed large and internally consistent improvements across every outcome family examined. Biomechanical exposure decreased on all observational indices (RULA, REBA, HAL) and in a composite risk index, perceived musculoskeletal symptoms (NMQ) fell materially, workplace organization (5S) rose by nearly one-fifth, flow accelerated with cycle time dropping by about 10% while stability improved, product quality improved with a ~37% relative reduction in defect rate, and perceived work capacity (WAI) increased. These effects were statistically precise, practically meaningful, and directionally aligned with the mechanisms targeted by the intervention adjustable geometry, improved part presentation and lighting, error-proofing, micro-recovery, and clearer standardized work embedded in daily management.

Importantly, the pattern of results speaks to joint optimization rather than a trade-off. In many lean implementations, efforts to increase throughput inadvertently intensify time pressure or awkward postures, raising discomfort and error risk. Here, the opposite occurred: as stations became more ergonomic and the environment more ordered, operators moved faster and produced fewer defects. This supports the ErgoLean premise that integrating ergonomics into value-stream thinking annotating the map with exposure indicators, co-designing changes with operators, and validating them through pilots can unlock system-level improvements that are resilient in day-to-day use. The broad leftward shift in quartiles for cycle time and the narrowing of exposure distributions suggest that benefits were not limited to a few outliers but accrued across the operator population, a hallmark of changes that are simple, adjustable, and well-governed.

The study carries several limitations. The pre–post design lacks a concurrent control group and is therefore susceptible to secular trends or Hawthorne effects. We mitigated these risks by focusing on paired within-person differences, using observational and self-report instruments in parallel, and triangulating with objective operational metrics; nonetheless, causal claims should be interpreted with appropriate caution. Measurement error is inherent to observational ergonomics and to self-report instruments; our use of trained assessors, brief video support, and inter-rater calibration was intended to reduce noise without imposing unsustainable burden. The composite risk index, while useful for prioritization, is a constructed measure with fixed weights and should be interpreted as a summary signal rather than a direct proxy for injury risk. Finally, the observation windows were not designed to maximize volume, which explains small differences in units produced and argues against over-interpreting totals.

Despite these caveats, the convergence of large paired effects across ergonomics, organization, flow, quality, and work ability offers strong evidence that well-designed, operator-involved changes can enhance both human and system outcomes. For practice, we recommend institutionalizing three governance elements that enabled sustainability during the study: (1) ergonomic acceptance criteria embedded in engineering change control, so that geometry and presentation are treated as first-class requirements; (2) visible daily management of wellbeing and flow metrics, ensuring drift is quickly detected and addressed; and (3) routine participatory gemba that empowers operators to surface residual pain points and propose micro-improvements.

Future work should extend the design in three directions. First, evaluate durability and dose–response using stepped-wedge or staggered rollout designs and longer follow-up, including tracking of clinical musculoskeletal outcomes and absenteeism. Second, test generalizability across product families and demand patterns, with attention to subpopulations (e.g., shorter/taller operators) to ensure equity of benefit. Third, augment the lightweight measurement set with targeted digital sensing only where it directly informs design decisions, and combine field data with discrete-event simulation to explore layout and staffing scenarios before physical changes are made. Cost–benefit analyses that integrate quality savings, productivity gains, and reduced discomfort would support scaling decisions.

The ErgoLean approach embedding ergonomics into value-stream analysis, co-designing changes with the people who do the work, and validating through rapid pilots appears to reduce biomechanical exposure and discomfort while simultaneously improving organization, speed, quality, and perceived work ability. For organizations pursuing Industry 5.0 aspirations, these findings suggest a practical path to human-centric resilience: design the work to fit the worker, and the system performs better as a consequence.

References

[1] Trstenjak M, Benešova A, Opetuk T, Cajner H. Human factors and ergonomics in industry 5.0 A Systematic literature review. Applied Sciences. 2025 Feb 17;15(4):2123.

[2] Ruiz de la Torre A, Borregan J, Pikatza N, Rio RM. Integrating human-centric simulations in educational production lines: advancing ergonomics

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

for industry 5.0 applications. International Journal of Production Management and Engineering. 2024 Jul 26;12(2):141-57.

[3] Rahardjo B, Wang FK, Lo SC, Chu TH. A sustainable innovation framework based on lean six sigma and industry 5.0. Arabian Journal for Science and Engineering. 2024 May;49(5):7625-42.

[4] Płaza G, Kabiesz P, Thatcher A, Jamil T. Ergonomics/Human Factors in the Era of Smart and Sustainable Industry: Industry 4.0/5.0. Management Systems in Production Engineering. 2025.

[5] Al-Zuheri A, Kaitan HS, Al Saffar IQ, Al-Zubaidi S. An evaluation of lean intervention combined with ergonomics on enhancing productivity and workplace risk reduction: a literature review. Industrial Engineering & Management Systems. 2023 Sep;22(3):259-72.

[6] Firescu V, Filip D. Human Factors and Ergonomics in Sustainable Manufacturing Systems: A Pathway to Enhanced Performance and Wellbeing. Machines. 2025 Jul 9;13(7):595.

[7] Gdoura R, Houssin R, Dhouib D, Coulibaly A. Design for lean 5.0: Integrating lean requirements and parameters into production systems in an industry 5.0 context. Concurrent Engineering. 2025:1063293X241312094.

[8] Bongomin O. Positioning Industrial Engineering in the Era of Industry 4.0, 5.0, and Beyond: Pathways to Innovation and Sustainability.

[9] Gdoura R. *Contribution to the integration of lean into the inventive design of manufacturing systems in the context of industry 5.0* (Doctoral dissertation, Université de Strasbourg; Université de Sfax (Tunisie)).

[10] Katariya M, Mathur A, Singh S. Human–Robot/Machine Interaction for Sustainable Manufacturing: Industry 5.0 Perspectives. InHandbook of Intelligent and Sustainable Manufacturing 2024 Aug 28 (pp. 18-41). CRC Press.

[11] Hasanain B. The role of ergonomic and human factors in sustainable manufacturing: A review. Machines. 2024 Feb 26;12(3):159.

[12] Bucci I, Fani V, Bandinelli R. Towards human-centric manufacturing: Exploring the role of human digital twins in industry 5.0. Sustainability. 2024 Dec 27;17(1):129.

[13] Andersén J. Optimizing the workforce for an assembly line: Human-centric approach towards Industry 5.0.

[14] Keshmiry A, Hassani S. Human-Centric Design Principles in Industry 4.0 and Industry 5.0. InComputational Intelligence for Analysis of Trends in Industry 4.0 and 5.0 2025 (pp. 275-290). Auerbach Publications.

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

[15] Tomelleri F, Sbaragli A, Piacariello F, Pilati F. Safe assembly in industry 5.0: Digital architecture for the ergonomic assembly worksheet. Procedia CIRP. 2024 Jan 1;127:68-73.
[16] Pereira AC, Alves AC, Arezes P. Augmented reality in a lean workplace at smart factories: a case study. Applied sciences. 2023 Aug 10;13(16):9120.
[17] Coulibaly A. Design for Lean 5.0: Integrating Lean Requirements and Parameters into Production Systems in an Industry 5.0 Context.
[18] Chen SC, Chen HM, Chen HK, Li CL. Multi-objective optimization in Industry 5.0: Human-centric AI integration for sustainable and intelligent manufacturing. Processes. 2024 Dec 2;12(12):2723.
[19] Chulakit S, Sadun AS, Jalaludin NA, Hashim H, Hassan H, Mahmood S, Marsi N, Fauzi MA. A Review of HRV and EEG Technology Applications in Industry 5.0: Emphasising Manufacturing Efficiency and Worker Well-Being. International Journal of Integrated Engineering. 2024 Sep 9;16(5):324-40.
[20] Vicente I, Godina R, Gabriel AT. Applications and future perspectives of integrating Lean Six Sigma and Ergonomics. Safety science. 2024 Apr 1;172:106418.
[21] Ghorbani E, Keivanpour S, Sekkay F, Imbeau D. Ergonomic assembly line balancing problems evolution and future trends with insights into industry 5.0 paradigm. Bureau de Montreal, Université de Montreal; 2023 Jun.
[22] Hien TN, Amdee N, Sangsongfa A. Achieving FIT Manufacturing Through the Lens of Industry 5.0? A Lean. InProceedings of the 1st International Conference on Sustainability and Emerging Technologies for Smart Manufacturing: SETSM 2024, 27–28 April, Hanoi, Vietnam 2025 Feb 13 (p. 327). Springer Nature.
[23] Singh T, Singh D, Singh CD, Singh K. Industry 5.0. Factories of the Future: Technological Advancements in the Manufacturing Industry. 2023 May 15:21-45.
[24] Cuevas C, Mira-Solves I, Verdu-Jover A. Industry 5.0's pillars and Lean Six Sigma: mapping the current interrelationship and future research directions. International Journal of Productivity and Performance Management. 2025 Mar 18;74(4):1347-64.
[25] Pawar PP, Hemamalini V, Kumari S, Tyagi AK. Industry 5.0: A New Industrial Revolution and Technological Applications. InComputational Intelligence for Analysis of Trends in Industry 4.0 and 5.0 (pp. 426-458). Auerbach Publications.

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

[26] Islam MT, Sepanloo K, Woo S, Woo SH, Son YJ. A review of the industry 4.0 to 5.0 transition: exploring the intersection, challenges, and opportunities of technology and human–machine collaboration. Machines. 2025 Mar 24;13(4):267.
[27] Ioniță AR, Anghel DC, Boudouh T. Mind, Machine, and Meaning: Cognitive Ergonomics and Adaptive Interfaces in the Age of Industry 5.0. Applied Sciences (2076-3417). 2025 Jul 15;15(14).
[28] Mehta AM, Rauf A, Senathirajah AR. Achieving world class manufacturing excellence: integrating human factors and technological innovation. Sustainability. 2024 Dec 20;16(24):11175.
[29] Sheikh RA, Ahmed I, Faqihi AY, Shehawy YM. Global perspectives on navigating Industry 5.0 knowledge: Achieving resilience, sustainability, and human-centric innovation in manufacturing. Journal of the Knowledge Economy. 2024 Dec 28:1-36.
[30] Keshmiry A, Hassani S. Human-Centric 11 Principles in Industry Design 4.0 and Industry 5.0. Computational Intelligence for Analysis of Trends in Industry 4.0 and 5.0. 2025 Jun 17:275.
[31] Kaswan MS, Chaudhary R, Garza-Reyes JA, Singh A. A review of Industry 5.0: from key facets to a conceptual implementation framework. International Journal of Quality & Reliability Management. 2025 Mar 11;42(4):1196-223.
[32] Hien TN, Amdee N, Sangsongfa A. Achieving FIT Manufacturing Through the Lens of Industry 5.0? A Lean Perspective. InInternational Conference on Sustainability and Emerging Technologies for Smart Manufacturing 2024 Apr 26 (pp. 327-336). Singapore: Springer Nature Singapore.
[33] Pierli G. Development of an Integrated Analysis Methodology for Lean Manufacturing and Sustainable Development in the Mechanical Engineering Industry.
[34] Trstenjak M, Đukić G, Opetuk T. Human Factors and Ergonomics in Logistics Activities by Principles of Industry 5.0. This document and the underlying event have been planned and executed as a part of the JOINOLOG research project. 2023 Nov 14:64.
[35] Ramírez de Arellano Gómez E. Enhancing worker well-being in electric vehicle manual assembly operations through ergonomic solutions and Industry 5.0 integration.
[36] Dehghan S, Sattarpanah Karganroudi S, Echchakoui S, Barka N. The integration of additive manufacturing into industry 4.0 and industry 5.0: a

Volume. 4 Issue No. 4 (2025)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

bibliometric analysis (trends, opportunities, and challenges). Machines. 2025 Jan 16;13(1):62.