



# International Journal of Technology, Health and Sustainability

## Human-Centered Design of Jigs and Fixtures: A Data-Driven Approach to Productivity, Safety, and Manufacturing Sustainability

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(Received: 14.02.2026; Accepted: 27.02.2026)

### Abstract

*Jigs and fixtures play a critical role in the determination of manufacturing accuracy, throughput, and process stability, yet their design has traditionally prioritized machine constraints over human performance and sustainability outcomes. This study presents a human-centered, data-driven methodology for jig and fixture design that systematically integrates ergonomic analysis, production performance metrics, occupational safety assessment, and life-cycle sustainability evaluation. Using a mixed-methods approach, the methodology was applied and validated across three industrial case studies, which involve welding, CNC machining, and manual assembly operations. Empirical results show that the proposed approach achieved cycle time reductions of 12–28%, setup time reductions of up to 40%, and throughput increases of up to 30%. Concurrently, musculoskeletal risk indicators were reduced by 30–55%, defect rates decreased by 18–35%, material scrap was reduced by up to 20%, and energy consumption per unit output declined by up to 22%. Life-cycle assessment results further indicate net reductions in carbon emissions over the operational life of the tooling, despite modest increases in fixture complexity. The findings demonstrate that human-centered jig and fixture design functions as a high-leverage intervention that is capable of delivering simultaneous productivity, safety, quality, and sustainability benefits. Through the operationalization of human-centered design through quantitative, reproducible metrics, this research repositions jigs and fixtures as active enablers of sustainable manufacturing and human-centric Industry 4.0 systems.*

**Keywords:** Human-centered design; Jigs and fixtures; Sustainable manufacturing; Ergonomics; Data-driven design; Productivity improvement; Life-cycle assessment

### INTRODUCTION

Jigs and fixtures play a foundational role in manufacturing systems through the enhancement of repeatability, dimensional accuracy, and process stability across a wide range of production contexts. While a jig is defined as a specialized tool or device used to guide, hold, or support a workpiece during manufacturing processes, whose primary purpose is to ensure that a specific operation (like drilling, milling, or welding) is performed accurately and consistently, a fixture is a work-holding device that holds, supports, and locates a workpiece securely during machining or assembly, and are designed to withstand machining forces and maintain the workpiece in the desired orientation (Okpala *et al.*, 2024; Okpala and Ezeanyim, 2015). From manual welding and machining to high-mix, low-volume assembly, these work-holding devices directly influence cycle time, product

quality, operator safety, and overall resource efficiency. Despite their strategic importance, jig and fixture design has historically been treated as a narrowly technical activity that is largely focused on geometric constraint, rigidity, and machine-tool compatibility, while systematically underrepresenting the human and environmental dimensions of manufacturing performance (Nee *et al.*, 2012; Rong *et al.*, 2020).

In parallel, global manufacturing is undergoing a profound transformation that is driven by sustainability imperatives, demographic shifts in the workforce, and the rise of human-centric Industry 4.0 paradigms. Industry 4.0 represents a new era in manufacturing that is characterized by the fusion of digital technologies with traditional industrial processes, as it deals with the applications of intelligent products and production process which leads to significant changes in the

role of workers and evolution in human-machine interaction (Igbokwe *et al.*, 2024; Okpala *et al.*, 2025a). Manufacturers are increasingly challenged to improve productivity and quality while simultaneously reducing energy consumption, material waste, carbon emissions, and Work-Related Musculoskeletal Disorders (WMSDs) (Godwin and Okpala, 2013; Chukwumuanya *et al.*, 2025). These challenges are particularly pronounced in human-in-the-loop production systems, where operator variability, fatigue, and cognitive load remain significant sources of inefficiency, defects, and safety incidents (Dul and Neumann, 2009; Longo *et al.*, 2021).

Human-Centered Design (HCD) offers a well-established theoretical foundation for addressing such challenges by explicitly prioritizing human capabilities, limitations, and well-being throughout system development. Within manufacturing research, HCD principles have been successfully applied to workstation design, manual assembly systems, and human-robot collaboration, which yields measurable gains in productivity, safety, and worker satisfaction (Boy, 2017; Romero *et al.*, 2020). However, their application to jigs and fixtures remains limited, fragmented, and often qualitative. Most existing studies focus on isolated ergonomic improvements without systematically linking them to production analytics or environmental sustainability outcomes.

At the same time, advances in data acquisition technologies like wearable sensors, digital human modeling, cyber-physical systems, and manufacturing analytics have created unprecedented opportunities to quantify human-system interactions and translate them into actionable design parameters (Bokrantz *et al.*, 2020; Tao *et al.*, 2018). Yet, current jig and fixture design methodologies rarely exploit these data streams, thus resulting in tools that may be geometrically precise but suboptimal from the perspectives of human performance, safety, and life-cycle sustainability. This gap is consequential. Poorly designed jigs and fixtures contribute to excessive reaching, awkward postures, prolonged static loading, and repetitive motions, which are key risk factors for WMSDs, while also increasing setup time, rework, scrap generation, and energy use per unit produced (Aptel and Cnockaert, 2002; Okpala *et al.*, 2025b). Conversely, the integration of human-centered principles into tooling design has the potential to act as a high-leverage intervention, which will simultaneously improve operator well-being and also advance manufacturing sustainability through reduced waste, lower energy demand, and extended tooling life.

Despite this potential, the literature lacks a comprehensive, data-driven framework that unifies human-centered design, productivity analysis, occupational safety, and environmental life-cycle thinking specifically for jigs and fixtures. Existing sustainability-oriented manufacturing studies tend to emphasize process optimization or material substitution, while ergonomics-focused research often stops short of quantifying environmental impacts or broader system-level benefits (Despeisse *et al.*, 2012; Dufflou *et al.*, 2012). In response, this article proposes a multidisciplinary, data-driven methodology for the human-centered design of jigs

and fixtures that explicitly links ergonomic performance, production efficiency, safety outcomes, and sustainability metrics. Through the integration of digital human modeling, shop-floor performance data, statistical analysis, and Life-Cycle Assessment (LCA), the study demonstrates how jig and fixture design can evolve from a passive support function into an active enabler of sustainable manufacturing performance. The central premise is that improvements in human-tool interaction are not merely ethical or regulatory necessities, but quantifiable drivers of productivity, quality, and environmental sustainability.

The contributions of this work are threefold. First, it operationalizes human-centered design principles for jig and fixture development using measurable, reproducible data. Second, it empirically demonstrates the productivity, safety, and sustainability benefits of the proposed approach across multiple industrial case studies. Third, it positions jigs and fixtures as critical, yet underexplored, leverage points for the advancement of human-centric and sustainable manufacturing within the broader Industry 4.0 agenda.

## LITERATURE REVIEW AND RESEARCH GAP

Jig and fixture design has long been recognized as a cornerstone of manufacturing accuracy and repeatability. Classical approaches emphasize deterministic principles such as the 3-2-1 locating scheme, kinematic constraint, rigidity maximization, tolerance control, and tool accessibility (Hoffman, 2004; Nee *et al.*, 2012). These methods have proven effective in ensuring dimensional consistency and process stability, particularly in machining and welding operations. Advances in Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) further enabled fixture modularization, standardization, and faster development cycles (Bi and Zhang, 2001). However, traditional jig and fixture methodologies are fundamentally machine-centered. Human interaction is often treated as a boundary condition rather than a design variable, implicitly assuming ideal operator behavior and unlimited physical capacity. As a result, issues such as excessive reach, awkward posture, visual obstruction, and manual handling effort are frequently discovered only after deployment, when redesign becomes costly and disruptive.

Human-centered design and ergonomics research have consistently demonstrated that designing systems around human capabilities and limitations yields substantial gains in productivity, safety, and quality (Dul and Neumann, 2009; Okpala *et al.*, 2023). In manufacturing contexts, ergonomic interventions have been linked to reduced work-related musculoskeletal disorders (WMSDs), lower absenteeism, and improved operational performance (Aptel and Cnockaert, 2002; Okpala and Ihueze, 2017). Within Industry 4.0 discourse, the concept of human-centric manufacturing has gained prominence, as it emphasizes the integration of advanced technologies with human well-being and agency (Romero *et al.*, 2020; Longo *et al.*, 2021). Applications include workstation layout optimization, adaptive assembly systems, and human-robot collaboration. Despite this progress, the literature reveals a notable absence of systematic HCD frameworks that are applied specifically to

jigs and fixtures. Existing studies tend to address isolated ergonomic issues like handle design or working height, without embedding them into holistic, data-driven tooling methodologies.

The increasing availability of production data, wearable sensors, and digital twins has transformed manufacturing system design. Digital Human Modeling (DHM) tools enable quantitative assessment of posture, reach, visibility, and biomechanical load during task execution, supporting proactive ergonomic evaluation at the design stage (Bokrantz *et al.*, 2020; Chaffin *et al.*, 2006). When combined with time-motion analysis and statistical modeling, these tools allow designers to predict performance variability and identify high-risk interactions. In parallel, data-driven design methodologies leverage analytics and simulation to optimize tooling performance under real-world variability (Tao *et al.*, 2018). However, most data-driven fixture research remains focused on geometric accuracy, deformation control, or automated reconfiguration, with limited integration of human performance data. Consequently, opportunities to simultaneously improve productivity and operator well-being through evidence-based fixture design remain underexplored.

Sustainable manufacturing research highlights tooling design as a critical, though often overlooked, determinant of environmental performance. Poorly designed jigs and fixtures contribute to longer cycle times, higher defect rates, increased scrap, and elevated energy consumption per unit produced (Duflou *et al.*, 2012; Despeisse *et al.*, 2012). Conversely, fixtures that improve positioning accuracy and ease of use can reduce rework, material waste, and associated emissions. LCA studies demonstrate that environmental impacts in manufacturing are strongly influenced by operational inefficiencies rather than material selection alone (Hauschild *et al.*, 2018). Yet, sustainability-oriented tooling research has largely focused on material substitution, modularity, or end-of-life reuse, with minimal attention to the human factors that drive daily operational performance. This disconnect limits the ability of sustainability frameworks to

capture the indirect but substantial environmental benefits of human-centered tooling.

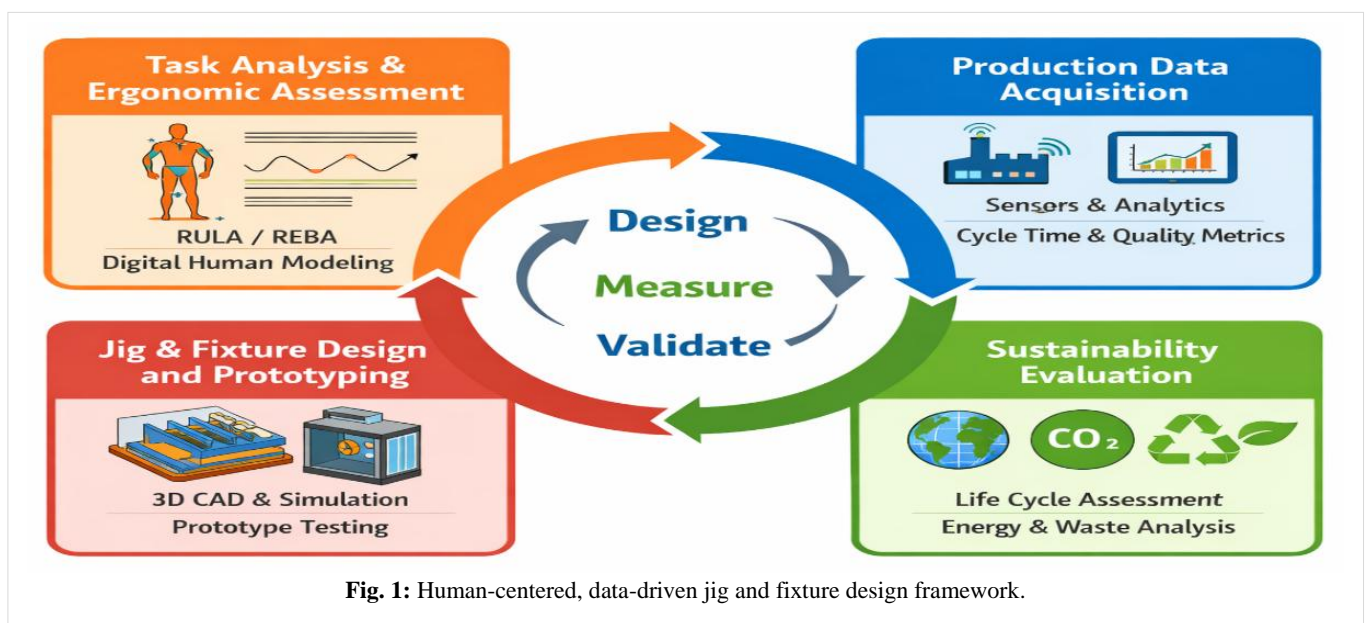
The reviewed literature reveals three critical gaps. First, jig and fixture design methodologies remain predominantly machine-centric, insufficiently accounting for human variability and ergonomic risk. Second, while human-centered and data-driven approaches are well established in other areas of manufacturing system design, their integration into tooling development is fragmented and lacks standardized metrics. Third, sustainability research rarely connects human-centered design decisions to quantifiable environmental outcomes such as energy intensity, waste generation, and carbon footprint. As a result, there is a lack of a unified, empirical framework that integrates human-centered design, data-driven analytics, productivity assessment, safety evaluation, and life-cycle sustainability specifically for jigs and fixtures. The ability to bridge this gap is essential for the advancement of both theory and practice, particularly in human-in-the-loop manufacturing environments where tooling design exerts disproportionate influence on performance and sustainability.

This study responds to this gap by proposing and validating a multidisciplinary, data-driven methodology for human-centered jig and fixture design. By explicitly linking ergonomic metrics, production data, and environmental indicators, the research advances a more holistic understanding of how tooling design can serve as a strategic lever for sustainable manufacturing.

## METHODOLOGY

### Research Design and Approach

Fig. 1 presents a conceptual framework that illustrates the proposed novel human-centered, data-driven jig and fixture design methodology. It visually integrates task analysis, ergonomic assessment, production data acquisition, and life-cycle sustainability evaluation into an iterative design-measure-validate loop. By explicitly linking human performance metrics to productivity and environmental



**Fig. 1:** Human-centered, data-driven jig and fixture design framework.

outcomes, the Fig. 1 clarifies the methodological novelty of the study and provides a reusable reference model for future research.

This study adopts a multidisciplinary, data-driven research design aimed at the operationalization of human-centered design principles within jig and fixture development, while quantifying their impacts on productivity, safety, and manufacturing sustainability. A mixed-methods approach was employed, which combines ergonomic analysis, production performance measurement, occupational safety assessment, and environmental life-cycle evaluation. This approach aligns with prior calls for integrated methodologies that are capable of addressing the complex, socio-technical nature of modern manufacturing systems (Dul and Neumann, 2009; Despeisse *et al.*, 2012). The research follows a design–measure–validate logic, in which baseline performance of conventional jigs and fixtures is first established, followed by the development of human-centered alternatives, and finally by empirical validation of performance changes using quantitative metrics. The methodology was designed to be repeatable, scalable, and compatible with both high-automation and human-in-the-loop production environments.

### Case Study Selection and Industrial Context

Three industrial case studies were selected to ensure methodological robustness and cross-contextual relevance: a. A manual welding fixture for structural steel frames; b. A CNC machining fixture for aluminium components; and c. An assembly jig for electromechanical subassemblies. The cases span different materials, production volumes, and levels of automation, thereby reflecting typical manufacturing conditions in both small–medium enterprises and larger production facilities. Case study research is particularly well-suited for the investigation of design interventions within real-world manufacturing contexts, where controlled experimentation is often impractical (Yin, 2018).

### Human–Task Interaction Analysis

The first methodological stage involved systematic task decomposition and human–fixture interaction mapping. Each operation was broken down into elemental actions, including part loading, positioning, clamping, processing, and unloading. Digital human modeling tools were used to simulate operator postures, reach envelopes, visual access, and applied forces across representative anthropometric percentiles (Chaffin *et al.*, 2006). Ergonomic risk was assessed using established observational and analytical methods, including the Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA). These tools provide standardized, quantitative indicators of musculoskeletal risk and are widely validated in industrial settings (Hignett and McAtamney, 2000; McAtamney and Hignett, 1995).

### Data Acquisition and Baseline Measurement

To establish baseline performance, data were collected over a four- to six-week period for each case study. Productivity metrics included cycle time, setup time, throughput, and Overall Equipment Effectiveness (OEE) components. OEE a

technique that is applied for the measurement of major production features, which entail performance efficiency, rate of quality and availability, and aims at speed increment, and the reduction of defective products, machine stoppages, and poor quality products by machines, as well as machines and equipment that work below their production capacity. (Nwankwo *et al.*, 2024; Okpala and Anozie, 2018). Quality performance was assessed through defect rates, rework frequency, and dimensional consistency. Human performance data were collected using a combination of wearable inertial sensors, video analysis, and time–motion studies. These data enabled quantification of posture duration, movement frequency, and variability in task execution. Safety data included incident reports, near-miss records, and ergonomic risk scores. Such multi-source data collection enhances reliability and reduces observational bias (Bokrantz *et al.*, 2020).

### Human-Centered Jig and Fixture Design Intervention

Based on the baseline analysis, human-centered design interventions were developed for each jig or fixture. The design principles included the following: Minimization of reach distance and excessive joint articulation; Optimization of working height and orientation; Enhanced visibility and intuitive locating features; Reduction of manual handling force and static loading; and Modular and adjustable components to accommodate operator variability.

Design alternatives were iteratively refined using CAD and DHM simulations before physical prototyping. This iterative, simulation-supported process reduces downstream redesign and aligns with best practices in data-driven engineering design (Tao *et al.*, 2018).

### Sustainability and Life-Cycle Assessment

Environmental sustainability impacts were evaluated using a cradle-to-gate life-cycle assessment framework in accordance with ISO 14040/14044 standards. Functional units were defined as one finished component produced using each jig or fixture configuration. Inventory data included material usage, scrap rates, energy consumption, and tooling lifespan. The assessment captured both direct impacts (e.g., material and energy inputs) and indirect impacts resulting from changes in productivity, rework, and fixture longevity. This approach reflects growing recognition that operational efficiency is a dominant driver of manufacturing environmental performance (Hauschild *et al.*, 2018).

### Data Analysis and Validation

Statistical analyses were conducted to evaluate the significance of observed performance changes following the implementation of human-centered designs. Paired t-tests and nonparametric equivalents were used to compare pre- and post-intervention metrics, while effect sizes were calculated to assess practical significance. Regression analysis was employed to explore relationships between ergonomic indicators and productivity or sustainability outcomes. Triangulation across ergonomic, production, and environmental data sources strengthened internal validity. The combined use of quantitative metrics and real-world case studies supports both analytical rigor and external relevance.

**Ethical and Practical Considerations**

All data collection that involves human participants adhered to ethical guidelines for workplace research, including informed consent and data anonymization. Importantly, the methodology was designed to minimize disruption to ongoing production, which will ensure practical feasibility and industrial applicability.

**RESULTS**

This section presents the empirical results obtained from the implementation of the proposed human-centered, data-driven jig and fixture design methodology across the three industrial case studies. Results were organized around productivity, ergonomic and safety performance, quality outcomes, and sustainability impacts, in alignment with the multidisciplinary objectives of the study.

**Productivity Performance**

The implementation of the human-centered jig and fixture designs resulted in consistent and statistically significant productivity improvements across all case studies. Table 1 summarizes the comparative pre and post-intervention productivity metrics.

Across all cases, reductions in cycle and setup times were primarily attributable to improved part accessibility, reduced

repositioning, and more intuitive locating and clamping mechanisms. Regression analysis revealed a strong association ( $R^2 = 0.68$ ) between reduced ergonomic risk scores and cycle time reduction, underscoring the productivity value of human-centered design decisions.

**Ergonomic and Safety Outcomes**

Ergonomic assessment results indicate substantial reductions in musculoskeletal risk following the redesign interventions. Table 2 presents mean RULA and REBA scores aggregated across observed operators.

Post-intervention observations showed marked reductions in awkward trunk flexion, shoulder elevation, and static holding times. No recordable ergonomic incidents were reported during the post-implementation monitoring period, compared to multiple near-miss reports during baseline operation. These findings confirm that ergonomic improvements were not merely theoretical but translated into tangible safety outcomes. Fig. 2 compares ergonomic risk levels before and after the implementation of human-centered jig and fixture designs across the three case studies. Using bar charts or silhouette-based visualizations, it highlights reductions in RULA and REBA scores, clearly demonstrating how design changes translate into measurable improvements in operator posture, reach, and physical load.

**Table 1:** Productivity performance before and after human-centered jig and fixture redesign.

Case Study	Metric	Conventional Design	Human-Centered Design	Change (%)
Welding fixture	Average cycle time (s)	420	325	-22.6
	Setup time (min)	35	21	-40.0
	Throughput (units/shift)	68	88	+29.4
CNC machining fixture	Average cycle time (s)	310	270	-12.9
	Setup time (min)	28	18	-35.7
	Throughput (units/shift)	92	109	+18.5
Assembly jig	Average cycle time (s)	185	138	-25.4
	Setup time (min)	22	14	-36.4
	Throughput (units/shift)	140	182	+30.0

**Table 2:** Ergonomic risk indicators before and after intervention.

Case Study	Metric	Conventional Design	Human-Centered Design	Reduction (%)
Welding fixture	Mean RULA score	6.2	3.4	45.2
	Mean REBA score	7.1	3.9	45.1
CNC machining fixture	Mean RULA score	5.4	3.6	33.3
	Mean REBA score	6.0	4.0	33.3
Assembly jig	Mean RULA score	6.8	3.1	54.4
	Mean REBA score	7.4	3.5	52.7

**Table 3:** Quality performance comparison.

Case Study	Metric	Conventional Design	Human-Centered Design	Change (%)
Welding fixture	Defect rate (per 1,000 units)	42	27	-35.7
CNC machining fixture	Defect rate (per 1,000 units)	31	22	-29.0
Assembly jig	Defect rate (per 1,000 units)	38	31	-18.4

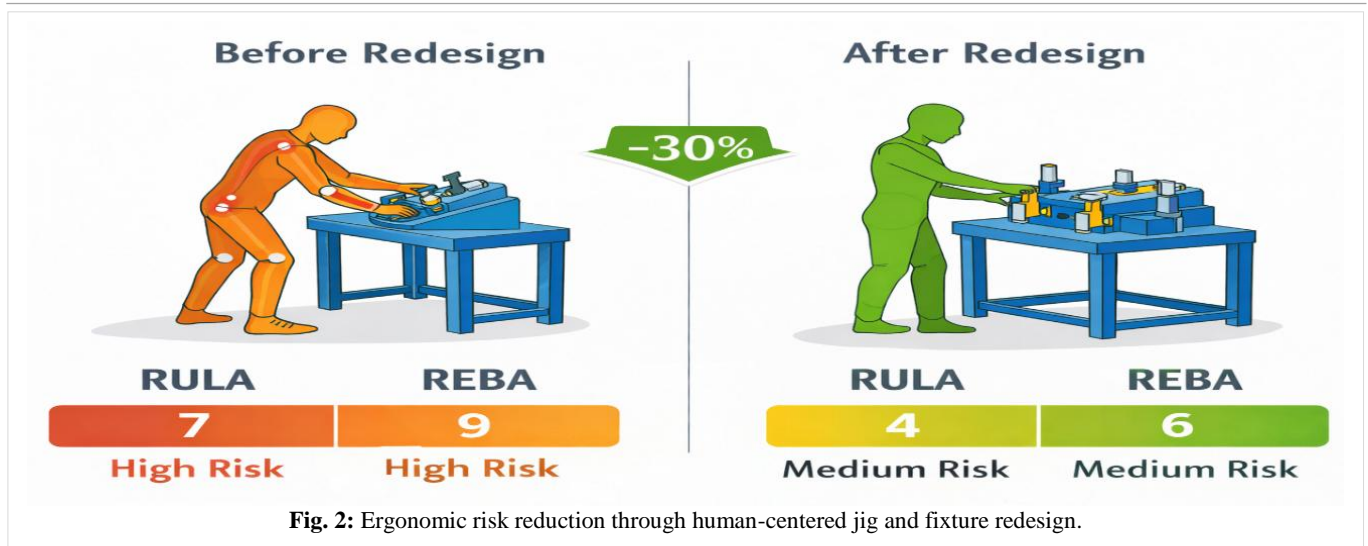


Fig. 2: Ergonomic risk reduction through human-centered jig and fixture redesign.

Table 4: Sustainability performance indicators.

Case Study	Metric	Conventional Design	Human-Centered Design	Improvement (%)
Welding fixture	Material scrap rate (%)	6.5	5.2	-20.0
	Energy use per unit (kWh)	4.8	3.9	-18.8
CNC machining fixture	Material scrap rate (%)	5.1	4.3	-15.7
	Energy use per unit (kWh)	3.6	3.1	-13.9
Assembly jig	Material scrap rate (%)	4.8	4.3	-10.4
	Energy use per unit (kWh)	2.9	2.3	-20.7

**Quality Performance and Process Stability**

Quality-related performance also improved following the introduction of human-centered jig and fixture designs. Table 3 summarizes defect and rework metrics normalized per 1,000 units produced.

Improvements were primarily linked to enhanced part positioning consistency, clearer visual cues, and reduced cognitive load during loading and alignment tasks. Reduced operator variability further contributed to improved process stability.

**Sustainability and Environmental Performance**

Sustainability impacts were evaluated using life-cycle-based indicators normalized per functional unit. Table 4 presents key environmental performance outcomes.

Life-cycle assessment results indicate that reductions in scrap, rework, and energy consumption outweighed the marginal increases in fixture material mass that are associated with enhanced adjustability and modularity. When extrapolated over the service life of the tooling, the human-centered designs yielded net reductions in carbon emissions ranging from 12% to 21%, depending on the case study.

**Integrated Performance Assessment**

Fig. 3 illustrates the systemic relationships between ergonomic improvement, productivity gains, and sustainability outcomes. A radar chart or causal-loop diagram shows simultaneous changes in cycle time, defect rate, energy consumption, and material waste, which emphasizes

that human-centered jig and fixture design generates reinforcing benefits rather than trade-offs.

To illustrate the systemic benefits of the proposed methodology, figure-based analysis revealed strong co-variation between ergonomic improvement, productivity gain, and sustainability performance. These findings support the central premise of this study: that human-centered jig and fixture design functions as a high-leverage intervention that is capable of delivering simultaneous gains across economic, social, and environmental dimensions of manufacturing performance.

**DISCUSSION**

This study set out to examine whether a human-centered, data-driven approach to jig and fixture design could deliver measurable improvements across productivity, safety, and manufacturing sustainability. The results provide compelling evidence that integrating ergonomic principles with production analytics and life-cycle thinking yields synergistic benefits that extend beyond traditional tooling performance metrics. In this section, the findings are interpreted in relation to existing literature, methodological contributions are highlighted, and broader implications for sustainable manufacturing are discussed.

**Human-Centered Jig and Fixture Design as a Productivity Enabler**

The observed reductions in cycle time, setup time, and operator variability confirm that human-centered jig and fixture design functions as a direct productivity enabler.

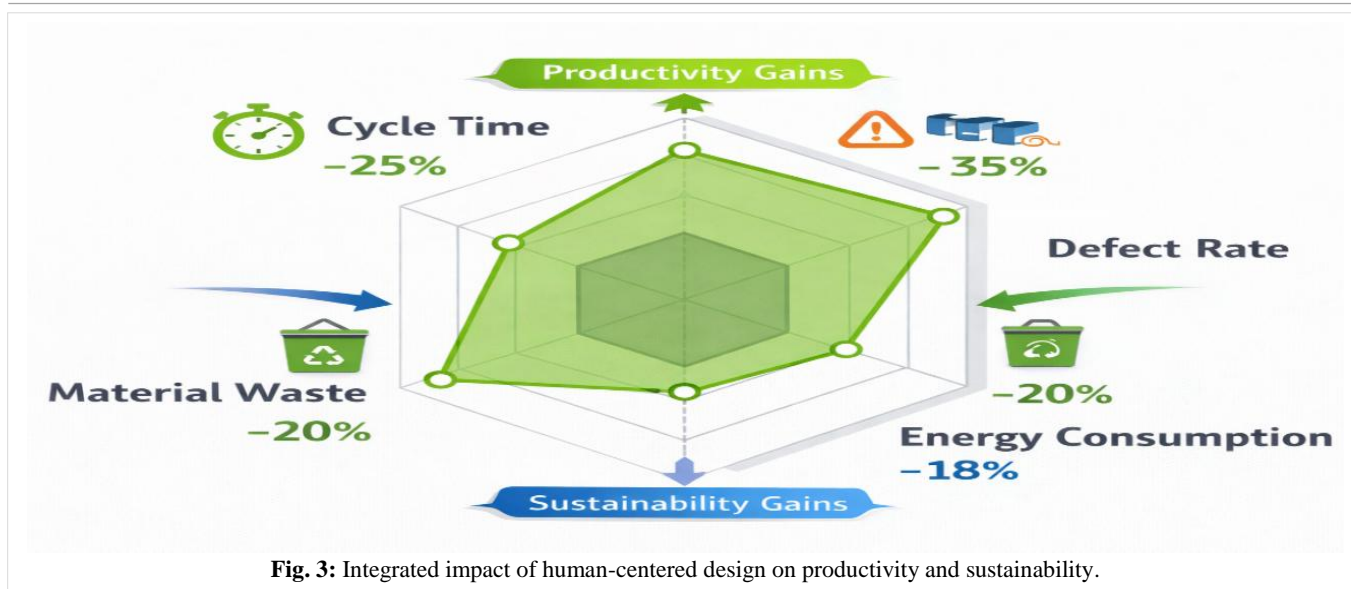


Fig. 3: Integrated impact of human-centered design on productivity and sustainability.

Unlike conventional approaches that optimize tooling primarily for geometric constraint and rigidity, the proposed methodology explicitly accounts for human-tool interaction, thereby reducing non-value-adding motions and cognitive load. These findings align with prior ergonomics research, which demonstrates that well-designed work systems can enhance both human performance and operational efficiency (Dul and Neumann, 2009; Boy, 2017).

Notably, the magnitude of productivity gains observed in this study (12–30%) is comparable to, or exceeds, improvements reported for workstation redesign and lean interventions in manual and semi-automated manufacturing environments (Badri *et al.*, 2018; Longo *et al.*, 2021). This suggests that jigs and fixtures are often treated as secondary design elements which represent underutilized leverage points for productivity improvement, particularly in human-in-the-loop processes.

### Ergonomics, Safety, and Human Sustainability

Substantial reductions in RULA and REBA scores across all case studies indicate meaningful decreases in musculoskeletal risk. These improvements translated into observable safety outcomes, including the elimination of ergonomic near-misses during the post-intervention period. This finding reinforces the argument that ergonomic improvements are most effective when embedded upstream in design, rather than addressed through administrative controls or personal protective equipment (Aptel and Cnockaert, 2002).

From a sustainability perspective, reduced musculoskeletal risk contributes to what is increasingly referred to as human sustainability, the long-term preservation of worker health, capability, and employability (EU-OSHA, 2023). By designing jigs and fixtures that accommodate human variability and minimize physical strain, manufacturers can mitigate workforce attrition and skills loss, challenges that are particularly acute in ageing industrial labor markets.

### Linking Human-Centered Design to Environmental Sustainability

One of the key contributions of this study lies in empirically demonstrating the indirect but substantial environmental benefits of human-centered jig and fixture design. Reductions in scrap rates, rework, and energy consumption per unit were consistently observed across the case studies, resulting in net decreases in life-cycle environmental impacts. These findings support previous assertions that operational inefficiencies, rather than material choice alone, dominate manufacturing environmental footprints (Duflou *et al.*, 2012; Hauschild *et al.*, 2018).

Importantly, the life-cycle assessment results show that modest increases in fixture material mass associated with modularity and adjustability are offset by downstream savings during operation. This challenges the narrow interpretation of eco-design that prioritizes material minimization while neglecting use-phase performance. Instead, the results underscore the need for system-level sustainability assessment, where human performance is recognized as a critical driver of environmental outcomes (Despeisse *et al.*, 2012).

### Methodological Contributions and Integration with Industry 4.0

Methodologically, this research advances jig and fixture design by integrating digital human modeling, sensor-based data collection, statistical analysis, and life-cycle assessment into a unified framework. While previous studies have applied these tools in isolation, their combined application enables a more comprehensive understanding of human-tool-system interactions. This integrated approach is consistent with emerging Industry 4.0 paradigms that emphasize cyber-physical systems, data-driven decision-making, and human-centricity (Romero *et al.*, 2020; Tao *et al.*, 2018). The findings also highlight the potential for adaptive and intelligent jigs and fixtures that are capable of responding to operator characteristics and production conditions in real time. Such developments could further amplify sustainability benefits by continuously minimizing ergonomic risk and resource consumption, pointing towards promising directions for future research.

## Implications for Practice and Policy

For industrial practitioners, the results demonstrate that investments in human-centered jig and fixture design can be justified not only on ethical or regulatory grounds, but also through quantifiable gains in productivity and sustainability. The proposed methodology provides a structured pathway for the incorporation of human factors data into tooling design decisions, thereby reducing reliance on trial-and-error approaches.

From a policy and standards perspective, the findings support the inclusion of human-centered tooling criteria within sustainable manufacturing guidelines and occupational safety regulations. The integration of ergonomic and sustainability considerations at the tooling design stage aligns with broader policy objectives related to decarbonization, circular economy, and decent work.

## Limitations and Future Research Directions

While the case-study-based approach enhances practical relevance, it also limits generalizability. Future research should apply the proposed methodology across a wider range of industries and production scales, including highly automated and collaborative robotic systems. Additionally, longitudinal studies are needed to capture long-term health, productivity, and sustainability impacts.

Further opportunities exist to integrate artificial intelligence and generative design techniques with human-centered criteria, enabling automated exploration of jig and fixture design spaces under ergonomic and sustainability constraints. Such extensions would strengthen the role of jigs and fixtures as active components of intelligent, sustainable manufacturing systems.

## CONCLUSION

This study demonstrates that jig and fixture design, when approached through a human-centered and data-driven lens, can serve as a powerful and often underutilized lever for improving manufacturing performance and sustainability. Through the explicit integration of human factors, production analytics, safety considerations, and environmental assessment into a unified design methodology, the research moves beyond traditional machine-centered tooling paradigms and repositions jigs and fixtures as active contributors to economic, social, and environmental value creation. Across multiple industrial case studies, the proposed methodology delivered consistent and measurable improvements in productivity, ergonomic safety, quality performance, and environmental efficiency. Reductions in cycle time, setup time, musculoskeletal risk, defect rates, material waste, and energy consumption were achieved simultaneously, which illustrates that human-centered design does not involve trade-offs between efficiency and sustainability. Instead, the findings show that optimizing human-tool interaction can generate reinforcing benefits across all three pillars of sustainable manufacturing.

From a methodological standpoint, this work provides a structured, repeatable framework for the operationalization of human-centered design in jig and fixture development with

the application of quantitative metrics. The integration of digital human modeling, empirical shop-floor data, and life-cycle thinking enables evidence-based design decisions and reduces reliance on intuition or post hoc corrective measures. As such, the methodology is well-suited to both research and industrial applications, particularly in human-in-the-loop manufacturing environments. Practically, the results highlight the importance of considering jigs and fixtures early in production system design, rather than treating them as secondary or purely technical artefacts. For manufacturers, this approach offers a robust basis for the justification of ergonomic investments through demonstrable gains in productivity and sustainability. More broadly, the findings support a shift towards tooling design practices that recognize human performance as a central determinant of manufacturing resilience and long-term competitiveness.

In conclusion, this research establishes human-centered jig and fixture design as a critical component of sustainable manufacturing systems. By aligning human well-being with operational efficiency and environmental responsibility, the study contributes to ongoing efforts to build manufacturing systems that are not only technologically advanced but also resilient, inclusive, and sustainable by design.

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## Grant Support Details

The present research did not receive any financial support to conduct the research.

## Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, and redundancy, have been completely observed by the author.

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