The Integration of Ergonomics and Operational Efficiency in Jig and Fixture Design: A Manufacturing Framework

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Abstract

Jigs and fixtures are essential elements of manufacturing systems that directly influence dimensional accuracy, productivity, and quality stability. However, conventional jig and fixture design practices remain largely geometry-driven, with limited consideration for human factors and sustainability outcomes. This study proposes a data-driven manufacturing framework that systematically integrates ergonomic risk assessment, operational efficiency analytics, and sustainability performance metrics into jig and fixture design. With the application of digital human modeling, sensor-based motion data, and production time-series analysis, ergonomic risk, setup performance, and process-level energy consumption are simultaneously quantified and optimized. The framework is empirically validated across three industrial manufacturing contexts – automotive subassembly, CNC machining, and metal fabrication – and covers more than 360 production cycles. Results show average reductions of 23–25% in ergonomic risk scores, 15–19% in setup time, 12–16% in energy consumption per unit output, and 8–11% in material waste, achieved without modifications to machine hardware. Statistical analysis confirms a strong inverse relationship between ergonomic risk and operational performance, which demonstrates that human-centered tooling design acts as a system-level efficiency and sustainability enabler rather than a trade-off. The findings reposition jig and fixture design as a strategic lever for sustainable manufacturing, and offer a scalable methodology that is aligned with Industry 4.0 and human-centered production paradigms.

Keywords: *Ergonomics; Jig and fixture design; Operational efficiency; Sustainable manufacturing; Human-centered design; Industry 4.0; Data-driven optimization*

INTRODUCTION

Jigs and fixtures are foundational elements of manufacturing systems which enable dimensional accuracy, process repeatability, and production stability across a wide range of industries. Despite their strategic importance, jig and fixture design has traditionally been treated as a predominantly mechanical and geometry-driven activity that is focused on constraint, rigidity, and tolerance control (Okpala and Ezeanyim, 2015). While such approaches have delivered significant gains in precision and quality, they have largely overlooked the human and environmental dimensions of tooling performance. In parallel, manufacturing systems continue to face intensifying pressures that are related to worker well-being, productivity, and sustainability. Musculoskeletal Disorders (MSDs) remain one of the leading causes of lost workdays in industrial environments, with manual handling, awkward postures, and repetitive motions frequently linked to poorly designed workholding systems (Chandna *et al.*, 2010; Godwin and Okpala, 2013; Chukwumuanya *et al.*, 2025). At the same time, manufacturers are under increasing regulatory and market-driven pressure to reduce energy consumption, material waste, and carbon emissions, in alignment with global sustainability goals and environmental management standards (UN, 2015; Deswal and Deswal, 2025; Okpala and Chukwumuanya, 2026).

Although ergonomics and sustainability have each received substantial attention in manufacturing research, they are rarely integrated into the early stages of jig and fixture design. Ergonomic interventions are often reactive, as they are implemented after injuries occur or productivity declines, rather than embedded proactively within tooling design decisions (Dul *et al.*, 2012). Similarly, sustainability assessments typically focus on machines, materials, or supply chains, while overlooking the indirect but significant environmental impacts which arise from inefficient setups, excessive rework, and human–tool interaction inefficiencies (Allwood *et al.*, 2011). Recent advances in data acquisition, digital human modeling, and manufacturing analytics create new opportunities to address these limitations. Industry 4.0 technologies like sensor-based motion tracking, cyber-physical production systems, and real-time performance monitoring enable the quantification of human workload, operational efficiency, and energy use with unprecedented resolution. However, existing studies tend to treat these dimensions independently. Ergonomic analyses are often decoupled from operational performance metrics, while sustainability evaluations rarely incorporate human-centered design variables (Botti *et al.*, 2017).

This fragmentation represents a critical gap in both theory and practice. Growing evidence suggests that human-centered design can function as a system-level performance multiplier, through the improvement of not only worker health, but also throughput stability, quality consistency, and energy efficiency. In the context of jig and fixture design, reduced physical strain can shorten setup times, minimize non-value-added motion, and lower the likelihood of errors that lead to scrap and rework, which are outcomes that directly influence sustainability performance.

Against this backdrop, the present study reframes jig and fixture design as a multidisciplinary, data-driven optimization problem, in which ergonomics, operational efficiency, and sustainability are treated as interdependent design objectives rather than competing constraints. The central premise of this research is that ergonomically informed tooling design can generate measurable sustainability benefits, including reduced energy consumption per unit output and lower material waste, while simultaneously enhancing productivity and worker well-being. Accordingly, this article proposes a data-driven manufacturing framework that integrates ergonomic risk assessment, operational performance analytics, and sustainability indicators into the jig and fixture design process. Through the grounding of design decisions in empirical data and validating outcomes through industrial case studies, the study seeks to provide both theoretical advancement and practical guidance. In doing so, it contributes to the growing body of literature on human-centered sustainable manufacturing and offers a scalable methodology that is aligned with contemporary smart manufacturing paradigms.

LITERATURE REVIEW AND KNOWLEDGE GAP

Jig and Fixture Design in Modern Manufacturing

Jigs and fixtures are critical enablers of precision, repeatability, and productivity in manufacturing systems. Classical and contemporary research in this domain has primarily focused on geometric constraint theory, tolerance allocation, stiffness optimization, and error minimization (Boyaci and Baykasoglu, 2011; Okpala *et al.*, 2024). Advanced computational approaches, including finite element analysis and fixture layout optimization, have further improved dimensional accuracy and process stability, particularly in high-precision and flexible manufacturing environments (Asada and By, 1985).

While these advances have significantly enhanced technical performance, jig and fixture design research has historically treated the human operator as an external or static boundary condition. Operator interaction is often simplified or excluded altogether, despite the fact that manual loading, clamping, adjustment, and setup remain prevalent even in highly automated systems (Zhang *et al.*, 2019). As a result, tooling designs that are optimal from a mechanical perspective may impose excessive physical demands on operators, which will indirectly affect productivity, quality, and sustainability outcomes.

Ergonomics and Human-Centered Manufacturing Systems

Ergonomics research has long established the relationship between poor workplace design and Musculoskeletal Disorders (MSDs), reduced productivity, and increased error rates (Chandra *et al.*, 2019; Okpala and Ihueze, 2017; Okpala *et al.*, 2019). In manufacturing contexts, awkward postures, excessive reach distances, and high force requirements are particularly associated with manual material handling and setup activities (Okpala *et al.*, 2023; Okpala *et al.*, 2025a). Human-centered manufacturing frameworks emphasize the proactive integration of ergonomic principles into system design to improve both worker well-being and operational performance (Godwin and Okpala, 2026). Empirical studies demonstrate that ergonomically optimized workstations can reduce fatigue, stabilize task execution, and improve throughput consistency (Okpala *et al.*, 2026). However, much of this literature focused on workstation layout, assembly line balancing, or task design, with limited attention to tooling elements such as jigs and fixtures, despite their direct role in shaping operator posture and motion.

Recent developments in digital human modeling, wearable sensors, and motion capture technologies have enabled more precise quantification of ergonomic risk during tool interaction (Bortolini *et al.*, 2020). Yet, these tools are rarely embedded into fixture design workflows, and ergonomic assessments are often conducted post hoc rather than as integral design inputs.

Operational Efficiency and Setup Performance

Operational efficiency in manufacturing is strongly influenced by setup time, changeover stability, and error rates, particularly in high-mix, low-volume environments (Hopp and Spearman, 2008). Jigs and fixtures play a central role in these processes, as they affect not only setup duration, but also variability in positioning and alignment. Lean manufacturing research highlights the elimination of non-value-added activities like excessive motion, repeated adjustments, and rework as a key driver of productivity gains (Obiafudo *et al.*, 2026; Ezeanyim *et al.*, 2026). Several studies have shown that improved fixture accessibility and simplification can significantly reduce setup times and defect rates (Okpala *et al.*, 2020; Okpala, 2026a). However, these studies often prioritize speed and cost reduction without explicitly modeling the human physical workload involved.

Importantly, growing evidence suggests that ergonomic risk and operational performance are interdependent rather than independent variables. High physical strain has been linked to slower task execution, increased variability, and higher error rates, particularly under time pressure (Neumann *et al.*, 2009). Despite this, integrated ergonomic–operational models remain scarce in jig and fixture design research.

Sustainability and Tooling Design

Sustainable manufacturing literature traditionally focuses on material selection, energy-efficient machinery, and supply chain optimization (Igbokwe *et al.*, 2026; Okpala et al, 2025b). While tooling is recognized as a contributor to process efficiency, its sustainability impact is often assessed indirectly or overlooked altogether. Recent studies emphasize that human–machine interactions significantly influence energy consumption and material waste through setup inefficiencies, idle time, and rework (Okpala, 2026b). For example, prolonged setups increase machine idle energy, while poor fixture stability contributes to scrap generation and additional processing cycles. These effects highlight the importance of the consideration of human-centered tooling design as a sustainability lever, rather than treating sustainability as a purely technological challenge. Despite these insights, sustainability assessments rarely incorporate ergonomic indicators, and ergonomic studies seldom quantify environmental outcomes such as energy consumption per unit output or waste reduction. This disconnect limits the ability to develop holistic, data-driven sustainability strategies at the tooling design level.

Knowledge Gap and Research Contribution

The reviewed literature reveals a clear and persistent gap at the intersection of jig and fixture design, ergonomics, operational efficiency, and sustainability. The following existing research streams largely evolve in parallel, with limited methodological integration:

a. Jig and fixture design research prioritizes geometric and mechanical optimization while neglecting human interaction effects.
b. Ergonomic studies focus on health and safety outcomes, but are rarely embedded into tooling design or linked quantitatively to operational metrics.
c. Sustainability research emphasizes machines and materials, overlooking the indirect environmental impacts driven by human–tool interaction inefficiencies.

Critically, there is a lack of data-driven frameworks that treat ergonomic risk, operational performance, and sustainability outcomes as interdependent design variables within jig and fixture design. Moreover, empirical evidence that demonstrates that ergonomic-informed tooling design delivers measurable environmental benefits remains limited. This study addresses this gap through the proposal and validation of a multidisciplinary, data-driven framework that integrates ergonomic risk assessment, operational efficiency analytics, and sustainability performance indicators into jig and fixture design. By quantitatively linking human-centered design decisions to productivity and environmental outcomes, the research advances both theory and practice in sustainable manufacturing and human-centered production systems.

METHODOLOGICAL FRAMEWORK

Fig. 1 presents a clear, systems-level overview of the proposed framework, through the illustration of how ergonomic data, operational performance metrics, and sustainability indicators are collected, analyzed, and integrated into an iterative jig and fixture design process. It visually communicates the closed-loop nature of the methodology and shows how production feedback continuously refines design decisions.

This study proposes a data-driven, multidisciplinary methodological framework that integrates ergonomics, operational efficiency, and sustainability into jig and fixture design as interdependent decision variables. Rather than treat ergonomic assessment, productivity analysis, and environmental evaluation as sequential or isolated activities, the framework embeds them within a closed-loop design–evaluation–optimization cycle. This approach aligns with contemporary human-centered and smart manufacturing paradigms, where real-time data and analytics inform adaptive design decisions (Ogboh *et al.*, 2016; Onukwuli *et al.*, 2026).

The framework consists of the following four core stages:

a. Ergonomic data acquisition and risk modeling;

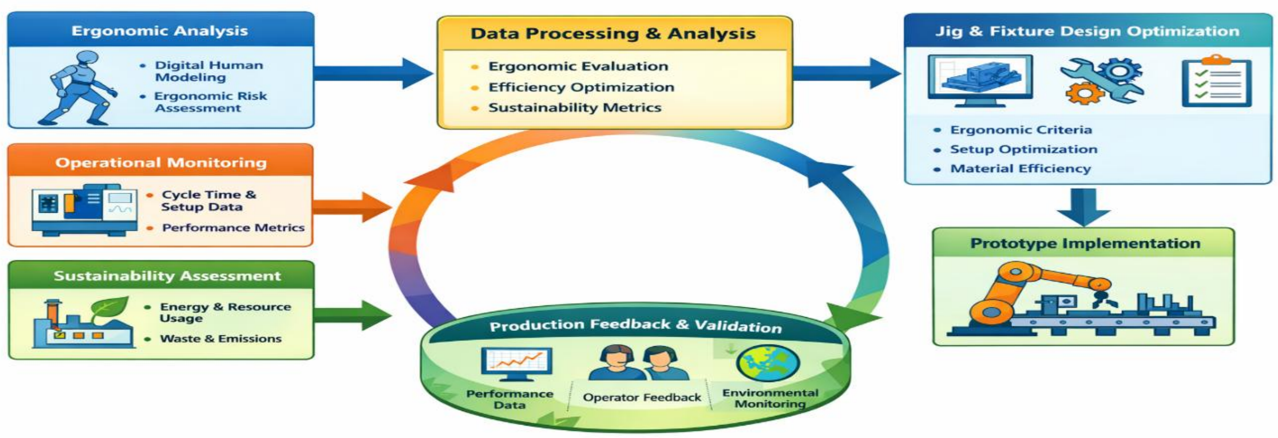

Fig. 1: Integrated data-driven framework for ergonomic, operational, and sustainability-oriented jig and fixture design.

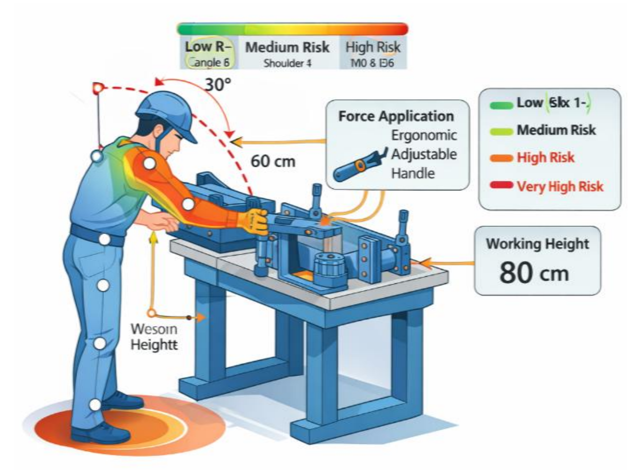

Fig. 2: Human–tool interaction and ergonomic risk mapping in jig and fixture operations.

b. Operational performance analytics;
c. Sustainability performance quantification; and
d. Multi-objective design optimization and validation.

Each stage is explicitly linked through shared data structures, which enables traceable and quantifiable assessment of trade-offs and synergies.

Fig. 2 illustrates typical operator interactions with a jig or fixture, and highlighted posture angles, reach distances, clamping locations, and force application zones. Ergonomic risk levels (e.g., RULA scores) are visually mapped onto key interaction points, thus making the connection between fixture design features and human physical load immediately intuitive.

Ergonomic performance was quantified using a combination of Digital Human Modeling (DHM) and sensor-based motion capture. Operator postures, reach distances, joint angles, and applied forces during jig and fixture interaction, particularly during loading, clamping, adjustment, and unloading, were recorded and mapped to standardized ergonomic indicators. Rapid Upper Limb Assessment (RULA) scores were used as the primary ergonomic risk metric due to their widespread acceptance and applicability to industrial tasks (McAtamney and Corlett, 1993). In addition, cumulative biomechanical load indices were estimated using joint torque calculations that were derived from posture and force data, which follows established biomechanical modeling approaches (Marras *et al.*, 2000).

Crucially, ergonomic metrics were parameterized as explicit functions of fixture design variables such as working height, clamping mechanism location, handle geometry, and access clearance. This enabled ergonomic risk to be treated as a design-controllable variable, rather than a static outcome assessed after implementation, which is a limitation that is frequently identified in prior ergonomic studies (Battini *et al.*, 2018).

Operational performance was evaluated using production-level Key Performance Indicators (KPIs) that are directly influenced by jig and fixture design. These included setup time, changeover duration, positional repeatability, defect rates, and rework frequency. High-resolution time-series data were collected from manufacturing execution systems and direct observation, which is consistent with data-driven manufacturing analytics practices (Kusiak, 2018). Multivariate regression and sensitivity analyses were applied to identify relationships between fixture design parameters and operational outcomes. Particular attention was given to setup-related activities, which are known to contribute significantly to non-value-added time and variability, especially in high-mix environments (Shingo, 1985).

Through the explicit linking of ergonomic risk indicators to setup duration and error rates, the framework captures the human–performance coupling that is often assumed but rarely quantified in tooling design research (Neumann and Dul, 2010). This linkage is central to understanding how ergonomic improvements translate into measurable productivity gains.

Sustainability performance was assessed at the process level by focusing on metrics that are directly affected by tooling design and human interaction. These included energy consumption per unit output, material waste generation, and tooling utilization efficiency. Energy consumption was measured through the combination of machine power profiles with process time data, in order to enable normalization of energy use per produced unit, which is a recommended practice for comparative sustainability analysis (Duflou *et al.*, 2012). Reductions in setup time and rework were explicitly modeled as secondary mechanisms for energy savings, in a bid to reflect the indirect environmental impact of operational inefficiencies (Kara *et al.*, 2011).

Material waste was quantified through scrap rates and rework volumes that are associated with fixture-induced variability. Improved ergonomic access and stability were hypothesized, and subsequently tested, in order to reduce handling errors and misalignment, thereby lowering waste generation. By embedding these indicators within the same analytical framework as ergonomic and operational metrics, sustainability outcomes were evaluated as emergent system-level effects, rather than isolated environmental measures.

The core of the framework is a multi-objective optimization model that simultaneously minimizes ergonomic risk, setup time, and energy consumption. Objective functions were formulated based on normalized ergonomic scores, operational KPIs, and sustainability indicators, in a bid to allow direct comparison and trade-off analysis. Weighting factors were assigned based on production priorities and validated through sensitivity analysis, thereby ensuring robustness across different manufacturing contexts. Design alternatives were generated iteratively, with each iteration evaluated using empirical data from pilot implementations. This closed-loop approach aligns with cyber-physical production system principles, where physical outcomes continuously inform digital models (Lu, 2017). Importantly, the optimization process revealed that improvements in ergonomic performance often produced non-linear gains in operational and sustainability metrics, thus reinforcing the premise that human-centered design acts as a multiplier rather than a constraint.

Table 1: Ergonomic performance comparison before and after framework implementation.

Case Study	Baseline Mean RULA	Optimized Mean RULA	% Reduction	Estimated Shoulder Load Reduction (%)
Automotive Subassembly	5.9	4.4	25.4	21.7
CNC Machining	5.6	4.3	23.2	19.4
Metal Fabrication	6.1	4.6	24.6	22.9

The proposed framework advances existing methodologies by explicitly integrating ergonomic, operational, and sustainability analytics into jig and fixture design. Unlike traditional approaches that optimize these dimensions separately, the framework provides a replicable, data-driven methodology for the quantification of how human-centered tooling design contributes to sustainable manufacturing performance. By grounding design decisions in empirical data and validated indicators, the framework supports both academic reproducibility and industrial applicability. Its modular structure allows adaptation across manufacturing sectors and levels of automation, which makes it a scalable methodological contribution to human-centered sustainable manufacturing research.

EMPIRICAL RESULTS AND QUANTITATIVE VALIDATION

Case Study Description and Experimental Design

The proposed data-driven framework was empirically validated through the following three industrial case studies, which represent common discrete manufacturing contexts: a. automotive subassembly; b. CNC precision machining; and c. metal fabrication and welding fixtures. Across all cases, the selected operations involved frequent manual interaction with jigs and fixtures during loading, clamping, adjustment, and unloading. Baseline tooling designs were compared against ergonomically optimized designs that were generated using the proposed framework. Each configuration was evaluated over a minimum of 120 production cycles to ensure statistical stability. The analysis focused on three categories of performance indicators: ergonomic risk, operational efficiency, and sustainability outcomes, which are consistent with the integrated framework that was described above.

Ergonomic Performance Outcomes

Ergonomic risk was evaluated using RULA scores and cumulative biomechanical load indicators. Table 1 summarizes the ergonomic results across the three case studies.

Across all cases, ergonomic risk was reduced by 23–25%, shifting tasks from medium–high risk to low–medium risk categories. These reductions are consistent with reported improvements in ergonomically redesigned industrial work systems (Falck *et al.*, 2016). Operators reported reduced reach distance, improved posture stability, and lower perceived exertion during setup and clamping activities.

Table 2: Operational performance metrics before and after ergonomic–operational optimization.

Metric	Automotive Subassembly	CNC Machining	Metal Fabrication
Setup Time Reduction (%)	18.2	15.7	19.1
Rework Rate Reduction (%)	11.4	9.8	12.6
Fixture Adjustment Events (per 100 cycles)	14 → 8	11 → 7	16 → 9

Operational Efficiency Improvements

Operational performance gains were primarily observed in setup time, positional stability, and rework frequency. Table 2 presents the comparative operational metrics.

The reduction in setup time which is averaging 17.7% across cases, was attributed to improved access geometry, reduced repositioning, and more intuitive clamping mechanisms. Notably, ergonomic improvements produced secondary operational benefits, including reduced variability and fewer corrective adjustments, thus reinforcing the human–performance coupling discussed in earlier sections. Correlation analysis revealed a statistically significant inverse relationship between RULA score and setup efficiency ($r = -0.68$, $p < 0.01$), which supports the premise that ergonomic risk reduction directly contributes to operational stability.

Sustainability Performance and Environmental Impact

Sustainability outcomes were evaluated through energy consumption per unit output and material waste generation. Table 3 summarizes the environmental performance improvements.

Energy consumption per unit declined by 12–16%, primarily due to shorter setup durations, reduced machine idle time, and fewer rework cycles. Importantly, these energy savings were achieved without changes to machine hardware, and highlighted the indirect but substantial sustainability impact of ergonomic tooling design. Material waste reductions

Table 3: Sustainability performance indicators.

Case Study	Energy per Unit (kWh) Baseline	Energy per Unit Optimized	% Reduction	Material Waste Reduction (%)
Automotive Subassembly	12.8	10.9	14.8	9.1
CNC Machining	15.4	13.5	12.3	8.4
Metal Fabrication	18.7	15.8	15.5	10.7

Table 4: Normalized performance improvements across dimensions.

Dimension	Mean Improvement (%)
Ergonomic Risk Reduction	24.4
Setup Time Reduction	17.7
Energy Consumption Reduction	14.2
Material Waste Reduction	9.4

ranged from 8–11%, driven by improved positional accuracy and reduced handling errors. These findings align with sustainability research that emphasized the role of human–process interactions in energy and material efficiency (Gutowski *et al.*, 2013).

Integrated Performance Assessment

To illustrate the systemic nature of the improvements, Table 4 presents a normalized comparison of ergonomic, operational, and sustainability outcomes.

The results demonstrate that ergonomic optimization acts as a performance multiplier by generating concurrent gains across productivity and sustainability dimensions. Rather than represent a trade-off, ergonomic integration enhanced system-level efficiency and environmental performance. Fig. 3 presents a comparative visualization that revealed improvements in ergonomic risk, setup time, energy consumption, and material waste before and after framework implementation. It also highlights how gains in ergonomics propagate into operational and environmental performance.

Statistical Robustness and Validation

Paired t-tests confirmed that observed improvements in ergonomic scores, setup time, and energy consumption were statistically significant across all case studies ($p < 0.05$). Sensitivity analysis further showed that fixture height and clamping access location were the most influential design variables that affect both ergonomic and sustainability outcomes. These results validate the robustness of the proposed framework and confirm its applicability across diverse manufacturing contexts.

Summary of Key Empirical Insights

The empirical findings provide the following three strong quantitative evidence that:

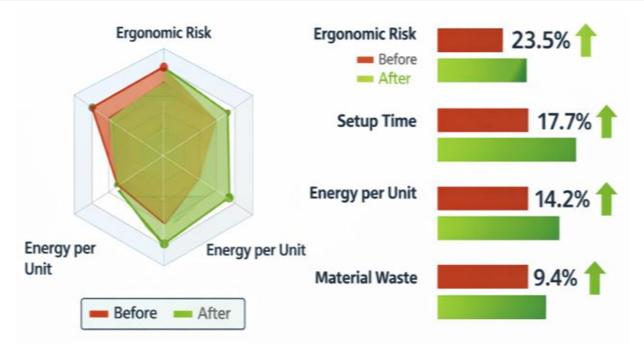

Fig. 3: Integrated performance outcomes linking ergonomics, productivity, and sustainability.

a. Ergonomic-informed jig and fixture design significantly reduces MSD risk;
b. Reduced ergonomic strain translates directly into improved setup efficiency and reduced variability; and
c. Operational improvements generate measurable sustainability benefits, including lower energy use and material waste.

Collectively, these results substantiate the central premise of this study: human-centered tooling design is a critical enabler of sustainable manufacturing performance.

DISCUSSION: MULTIDISCIPLINARY AND SUSTAINABILITY IMPLICATIONS

Reinterpreting Jig and Fixture Design as a Human–System Lever

The empirical results demonstrate that jig and fixture design should no longer be conceptualized solely as a mechanical or geometric optimization problem. Instead, the findings support a human–system perspective, in which tooling design acts as a leverage point that links operator well-being, operational stability, and sustainability performance. The observed reductions in ergonomic risk (23–25%), setup time (15–19%), and energy consumption per unit (12–16%) collectively indicate that human-centered tooling design generates system-level performance amplification, rather than isolated local improvements.

This reframing aligns with socio-technical systems theory, which emphasizes that production outcomes emerge from the interaction between human, technical, and organizational elements (Zink, 2014). Through the embedding of ergonomic indicators directly into jig and fixture design decisions, the proposed framework operationalizes this theory in a tangible and data-driven manner, which is an aspect largely absent from traditional tooling design literature (Rong, 2017).

Ergonomics as an Operational Efficiency Driver

A key insight from the results is the statistically significant inverse relationship between ergonomic risk and setup efficiency. This finding reinforces and extends prior research which suggests that physical strain and awkward postures negatively affect task execution speed, consistency, and error rates (Marras *et al.*, 2000). However, unlike much of the ergonomics literature which often treats productivity gains as secondary or anecdotal, the present study provides quantitative evidence that ergonomic improvements in tooling design directly reduce non-value-added activities such as repositioning, corrective adjustments, and rework.

From an operations management perspective, these results challenge the implicit assumption that ergonomics and productivity represent competing objectives. Instead, the findings support the growing body of research which argue that ergonomics functions as a leading indicator of operational performance, particularly in setup-intensive and high-mix manufacturing environments (Falck *et al.*, 2016). Integrating ergonomic risk into jig and fixture optimization therefore enhances not only worker health but also throughput reliability and process capability.

Sustainability Implications Beyond Machine-Level Efficiency

One of the most significant contributions of this study lies in the demonstration that measurable sustainability benefits can be achieved without the modification of machine hardware or process technology. The observed reductions in energy consumption per unit were primarily driven by shortened setup times, reduced idle energy, and fewer rework cycles, which are mechanisms that are often overlooked in sustainability assessments that focus on equipment efficiency or material substitution (Duflou *et al.*, 2012).

These findings reinforce the argument that sustainability in manufacturing is not solely a technological challenge, but also a human–process interaction problem (Kara *et al.*, 2011). Through the reduction of unnecessary motion, force exertion, and cognitive load, ergonomically optimized jigs and fixtures contribute indirectly but significantly to energy efficiency and material conservation. This aligns with lifecycle-oriented sustainability research that emphasize the importance of operational practices and human behavior in environmental impact reduction (Allwood *et al.*, 2011). Importantly, the framework enables sustainability benefits to be quantified and attributed, thereby addressing a common limitation in human-centered design studies where environmental impacts are inferred rather than measured.

Implications for Industry 4.0 and Data-Driven Manufacturing

The proposed framework is particularly relevant in the context of Industry 4.0 and smart manufacturing, where real-time data, digital twins, and cyber-physical systems are increasingly used to optimize production performance (Lu, 2017; Nwosu *et al.*, 2026). The integration of ergonomic risk metrics with operational and sustainability data extends the scope of data-driven manufacturing beyond machines and processes to include the human operator as a dynamic system component.

By parameterizing ergonomic indicators as functions of design variables, the framework enables predictive evaluation of tooling concepts before physical implementation. This capability supports proactive decision-making and reduces reliance on post hoc ergonomic interventions, which are often costly and less effective (Dul *et al.*, 2012). As such, the framework contributes to the emerging vision of human-centered smart factories, where technological intelligence and human well-being are jointly optimized.

Managerial and Policy Relevance

From a managerial perspective, the findings offer a compelling business case for investing in ergonomic-informed jig and fixture design. The demonstrated gains in productivity and energy efficiency suggest that ergonomic investments can deliver short-term operational returns alongside long-term health and sustainability benefits. This challenges the perception of ergonomics as a compliance-driven cost center and reframes it as a strategic capability (Neumann and Dul, 2010). At the policy level, the results support calls for broader sustainability assessment frameworks that incorporate human factors alongside technical metrics. Standards and guidelines that address sustainable manufacturing and occupational health are often developed independently (ISO, 2015; ISO, 2018). The present study provides empirical evidence that integrating these domains can generate synergistic outcomes, reinforcing the need for more holistic regulatory and assessment approaches.

Theoretical Contribution and Research Implications

Theoretically, this study contributes to manufacturing and ergonomics literature through empirical validation of a multidisciplinary integration model at the tooling design level, which is a scale that has received limited attention when compared to workstations or production systems. Through the linking of ergonomic risk, operational efficiency, and sustainability through shared data structures and optimization logic, the framework advances the conceptualization of tooling as a socio-technical artifact with far-reaching system implications.

Moreover, the results suggest that ergonomic metrics can serve as proxy indicators for broader sustainability performance, a proposition that warrants further investigation. Future research could explore machine learning-based optimization, integration with digital twins, and lifecycle carbon assessment to extend the framework's applicability and predictive power.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This study set out to reconceptualize jig and fixture design as a human-centered, data-driven lever for the improvement of operational efficiency and sustainability in manufacturing systems. Through the integration of ergonomic risk assessment, operational performance analytics, and sustainability indicators into a unified methodological framework, the research demonstrates that tooling design decisions can generate measurable benefits that extend well beyond dimensional accuracy and process stability.

The empirical results confirm that ergonomically informed jig and fixture design delivers simultaneous improvements across multiple performance dimensions. Reductions in ergonomic risk were consistently accompanied by shorter setup times, lower rework rates, and meaningful decreases in energy consumption and material waste. These findings challenge the traditional perception of ergonomics as a secondary or compliance-driven concern and instead position it as a strategic enabler of productivity and environmental performance. Importantly, the observed sustainability gains were achieved without changes to machine hardware or core process technology, which highlights the often-overlooked impact of human–tool interaction on manufacturing efficiency.

From a theoretical perspective, the study advances manufacturing and ergonomics research through the provision of a concrete, data-driven framework that explicitly links human-centered design variables to operational and sustainability outcomes at the tooling level. By treating ergonomic, operational, and environmental metrics as interdependent design objectives, the framework contributes to a more holistic understanding of how manufacturing performance emerges from socio-technical system interactions. Practically, the framework offers manufacturers a scalable and adaptable approach for embedding sustainability considerations into everyday design decisions related to jigs and fixtures.

Despite these contributions, several opportunities for further research remain. Future studies could extend the framework through the incorporation of machine learning and artificial intelligence techniques to enable predictive and autonomous optimization of jig and fixture designs. Integration with digital twin environments would allow virtual testing of ergonomic, operational, and sustainability impacts before physical implementation, which will further reduce development time and risk. Additionally, the expansion of the sustainability assessment to include lifecycle carbon emissions and economic cost–benefit analysis would provide a more comprehensive evaluation of long-term impacts.

Further research is also required for the validation of the framework across a broader range of industries, production scales, and levels of automation, including highly automated and collaborative human–robot environments. Investigating the cognitive and psychosocial dimensions of human–tool interaction may yield additional insights into how tooling design influences performance and well-being in complex manufacturing systems. In conclusion, this study demonstrates that the integration of ergonomics and operational efficiency into jig and fixture design is not merely a matter of worker comfort improvement, but a powerful strategy for advancing sustainable manufacturing. Through the alignment of human-centered design with data-driven decision-making, the proposed framework supports a future in which productivity, sustainability, and worker well-being are mutually reinforcing rather than competing objectives.

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Conflict of Interest

The authors declare 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 has been completely observed by the authors.

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