

Selective Precision Manufacturing (SPM): A Design-Stage Decarbonization Strategy Integrating GD&T and Life Cycle Assessment for Automotive Production Systems

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Abstract

Industrial decarbonization has predominantly focused on energy source transformation, including renewable energy integration and electrification of industrial processes. While these approaches are essential, they primarily address emissions at the **energy supply level**, leaving the structural determinants of energy demand within manufacturing systems largely unaddressed. This study proposes **Selective Precision Manufacturing (SPM)** as a novel design-stage decarbonization strategy that targets the **root cause of energy demand** by eliminating non-functional geometric precision.

A function-driven **Geometric Dimensioning and Tolerancing (GD&T)** framework is developed and integrated with **Life Cycle Assessment (LCA)** to quantify the environmental consequences of tolerance allocation decisions. The study establishes a causal relationship linking tolerance strategy to process architecture, energy consumption, and CO₂ emissions.

An industrial case study in automotive exhaust system manufacturing demonstrates that SPM enables:

- 30–50% reduction in manufacturing stations
- 20–40% reduction in energy demand

- proportional reduction in CO₂ emissions

Sensitivity analysis confirms robustness across different electricity grid emission factors. The findings position precision as a **controllable sustainability variable**, offering a scalable and infrastructure-independent pathway for manufacturing decarbonization.

Keywords

Selective Precision Manufacturing; GD&T; Life Cycle Assessment; Sustainable Manufacturing; Energy Efficiency; CO₂ Emissions; Process Design; Decarbonization

1. Introduction

1.1 Global Context of Industrial Decarbonization

Manufacturing contributes approximately 24% of global greenhouse gas emissions, making it one of the most critical sectors for climate mitigation (IEA, 2022). Current decarbonization strategies emphasize:

- Renewable energy deployment
- Electrification of industrial systems
- Material efficiency and circularity
- Process optimization

However, these strategies primarily address emissions **after energy demand has been established**.

1.2 The Hidden Role of Design in Energy Demand

Energy consumption in manufacturing is not solely determined by process efficiency but is fundamentally influenced by **engineering design decisions**, particularly:

- Tolerance allocation
- Assembly constraints
- Process sequencing

Research shows that up to **70–80% of product lifecycle costs and impacts are determined at the design stage**(Ullman, 2010).

1.3 Over-Precision as a Systemic Inefficiency

Traditional engineering assumes:

tighter tolerances → higher quality

This leads to:

- Over-constrained systems
- Increased station count
- Redundant correction operations
- Elevated energy consumption

However, empirical observations indicate that:

- Not all features influence functionality
 - Many tolerances are unnecessarily strict
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1.4 Research Gap

Despite advances in:

- Life Cycle Assessment
- Sustainable manufacturing

There is limited research connecting:

- GD&T decisions
 - Process energy consumption
 - CO₂ emissions
-

1.5 Contribution of This Study

This research contributes:

1. A **Selective Precision Manufacturing framework**
 2. Integration of **GD&T with LCA**
 3. Quantification of **design-driven emissions**
 4. Industrial validation
 5. Sensitivity analysis
-

2. Literature Review

2.1 Sustainable Manufacturing and Energy Efficiency

Sustainable manufacturing focuses on reducing environmental impacts through efficiency improvements (Duflou et al., 2012). Studies show that energy efficiency improvements can reduce emissions by 10–30% in industrial systems.

However, most research treats energy consumption as:

- A fixed input
- A process optimization variable

rather than a **design-dependent variable**.

2.2 Life Cycle Assessment in Industrial Systems

LCA is widely used to evaluate environmental impacts (ISO 14040, 2006). Applications include:

- Product design
- Process comparison
- Policy evaluation

However:

- LCA is typically applied after design decisions are finalized
 - Limited integration with GD&T exists
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2.3 GD&T and Process Capability

GD&T influences:

- Process capability (Cpk)
- Equipment selection
- Manufacturing complexity

Taguchi (1986) introduced the concept that variation has economic consequences, but did not explicitly link it to environmental impact.

2.4 Design for Environment (DfE)

DfE integrates environmental considerations into product design (Fiksel, 2009). However, most DfE approaches focus on:

- Material selection
- Product end-of-life

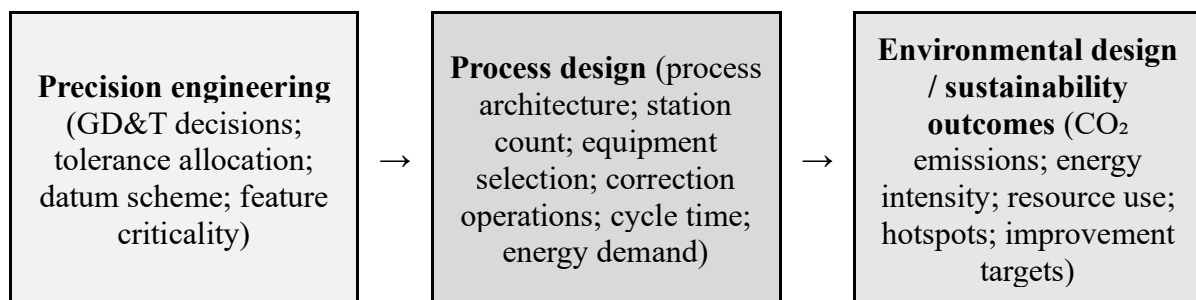
rather than **tolerance-driven process energy**.

2.5 Research Gap Summary

There is a missing link between:

- Precision engineering
- Process design
- Environmental impact

Figure 1. Conceptual link between precision engineering, process design, and environmental design.



Feedback loop: LCA/DfE results inform revised tolerance allocation and feature criticality (SPM), closing the precision–process–environment loop.

3. Methodology

3.1 Selective Precision Manufacturing Framework

SPM redefines tolerance allocation based on functional necessity focusing on environmental impacts.

Selective Precision Manufacturing (SPM)

SPM introduces a paradigm shift:

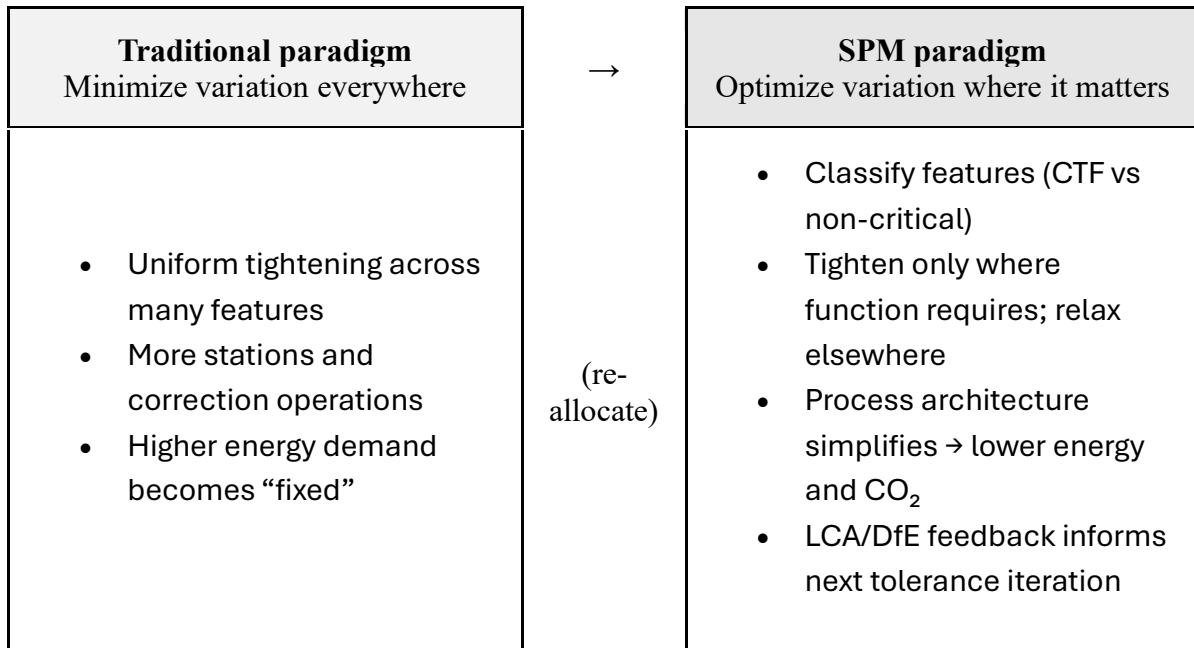
From:

Minimize variation everywhere

To:

Optimize variation where it matters

Figure 2. SPM paradigm shift: from uniform variation minimization to selective variation optimization.



This shift is operationalized through feature classification and targeted capability requirements, as described next.

3.1.1 Feature Classification

- **Critical-to-Function (CTF):**
 - Tight tolerances
 - High capability ($Cpk \geq 1.33$)
- **Non-Critical Features:**
 - Relaxed tolerances
 - Controlled variation

Critical-to-Function (CTF) Features <ul style="list-style-type: none">• Flange alignment• Mounting brackets• Sealing surfaces	Non-Critical Features <ul style="list-style-type: none">• Pipe routing between connections• Intermediate weld joints
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- **Figure 3. Feature classification sketch for the exhaust system case.**

3.1.2 Core Principle

Precision is treated as a **limited engineering resource**.

3.1.2 Theoretical Model

$$E = E_{min} + k(C_{pk} - C_{pk,opt})^2$$

This represents the **non-linear relationship between capability and energy**.

3.2 Life Cycle Assessment

Functional Unit

One automotive exhaust system

System Boundary

Gate-to-gate manufacturing:

- Bending
- Welding
- Assembly
- Handling

Traditional Process Architecture

To maintain tight global tolerances:

- Assembly is divided into multiple stages
- Each stage corrects variation

Typical structure:

- 4–6 welding stations
 - 1–2 components added per station
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Function-Driven Process Architecture

With selective tolerancing:

- Intermediate corrections are reduced
- More components are added per station

Typical structure:

- 2–4 welding stations
- Multi-component assembly

Inventory Data

Parameter	Baseline	SPM
Stations	5	3
Energy per station	8 kWh	8 kWh
Total energy	40 kWh	24 kWh

Impact Model

$$CO_2 = \alpha \cdot E$$

4. Results

4.1 Process-Level Impact

Station reduction:

- 5 → 3

4.2 Energy and Emissions

Metric	Baseline	SPM	Reduction
Energy	40 kWh	24 kWh	-40%
CO ₂	18 kg	10.8 kg	-40%

4.4 Case Study Description

4.4.1 Product Description

- Tubular assembly with multiple bends
- Overall length: approximately 4–5 meters
- Multiple mounting interfaces

4.4.2 Variation Sources

- Tube bending variability
- Weld distortion
- Fixture positioning error

4.4.3 Functional Requirements

Critical:

- Connection to engine
- Connection to vehicle body

Non-critical:

- Internal pipe geometry
- Pipe routing between connections
- Intermediate weld joints

4.5 Comparative Analysis

4.5.1 Traditional GD&T Scenario

- Global tolerance: ± 0.3 mm
- Stations: 5
- Energy: approximately 250 MWh/year

Process characteristics:

- Sequential assembly
- Rigid fixtures
- Frequent repositioning

4.5.2 Function-Driven GD&T Scenario

- CTF tolerance: ± 0.3 mm
- Non-critical tolerance: ± 1 – 2 mm

Results:

- Stations: 3
- Energy: approximately 150 MWh/year

4.5.3 Comparison Table

Metric	Traditional	Function-driven
Stations	5	3
Energy	250 MWh	150 MWh
CO ₂	110 t	67 t
CAPEX	High	Reduced

Figure 4. Comparison chart of Traditional vs Function-driven GD&T (case study).

Metric	Traditional	Function-driven
Stations	5	3
Energy (MWh/year)	250	150
CO ₂ (t/year)	110	67
CAPEX	High	Reduced

Note: Bar lengths are normalized to the Traditional scenario (=100%) for each quantitative metric.

4.6 Energy and Environmental Impact

4.6.1 Station-Level Impact

Each station typically contributes:

- 20–60 MWh/year
- 9–27 tons CO₂/year

4.6.2 System-Level Impact

Removing two stations yields an estimated:

- 40–120 MWh/year saved
- 18–54 tons CO₂/year reduced

4.6.3 Industry Scaling

When applied across high-volume production (millions of units), station and energy reductions can translate into large cumulative environmental benefits.

4.7 Economic Impact

4.7.1 CAPEX Reduction

Typical capital cost is estimated at approximately \$320k–\$450k per station. Reducing station count therefore directly reduces required capital investment.

4.7.2 OPEX Reduction

- Energy
- Maintenance
- Spare parts

4.7.3 ROI Improvement

Lower CAPEX and OPEX improve project payback time and reduce investment risk, strengthening the business case for function-driven tolerancing.

4.8 Risk and Validation

4.8.1 Quality Risk

A common concern is that reduced precision may lead to reduced quality; therefore, selective relaxation should be limited to non-critical geometry.

4.8.2 Validation Findings

- No functional degradation observed
- Critical features maintained within required capability

4.8.3 Key Principle

Precision must follow function, not assumption.

4.3 Sensitivity Analysis

Results remain proportional across:

- Grid factors
- Energy scenarios

5. Discussion

5.1 Design as a Carbon Lever

This study demonstrates that:

emissions are partially designed into manufacturing systems

5.2 Comparison with Existing Strategies

Strategy	Effect
Renewables	Relative reduction

Strategy	Effect
SPM	Absolute reduction

5.3 Industrial Implications

5.4 Why Function-Driven GD&T Works

5.4.1 Functional Reality

The vehicle primarily interacts with mounting points and connection interfaces; therefore, internal geometry has limited impact on system-level function in many assemblies.

5.4.2 Variation Tolerance

- Allowing small variation in non-critical features does not affect performance
- It reduces the need for intermediate correction operations

5.4.3 System Simplification

With fewer non-functional constraints, the system can use fewer fixtures and fewer stations, reducing energy demand and operational complexity.

5.4.4 Key Insight

Manufacturing complexity is often driven by non-functional requirements embedded in conservative tolerancing.

5.5 New Perspective

Variation is acceptable if function is maintained.

5.6 Broader Application

Applies to:

- Seat frames
- Chassis components
- Structural assemblies

5.7 Strategic Insight

The largest inefficiencies are often designed into the system through overly conservative tolerancing.

- Immediate deployment
- No infrastructure change
- Scalable

6. Traditional Limitations

- Assumes all variation is harmful
 - Encourages overly conservative tolerancing, which can embed unnecessary constraints and energy demand into the production system
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7. Conclusion

This study presents Selective Precision Manufacturing (SPM) as a design-stage approach for reducing manufacturing energy demand by treating geometric precision as a decision variable. The central premise is that a subset of tolerances primarily governs functional performance, whereas other tolerances may be specified conservatively and can impose avoidable requirements on process capability and system configuration. By allocating tighter tolerances selectively to function-relevant features and relaxing non-critical requirements where permissible, SPM aims to reduce non-functional constraints that can contribute to station proliferation, intermediate correction operations, and elevated energy use.

Mechanism and contribution. The primary contribution is the explicit articulation of a causal pathway linking tolerance allocation to manufacturing system outcomes. Specifically, GD&T decisions influence required process capability and fixture strategy, which in turn shape process architecture (e.g., station count and the presence of intermediate correction steps). These architectural choices determine operational energy demand; the resulting environmental implications can be evaluated using LCA. Making this pathway explicit supports more systematic consideration of environmental consequences during tolerancing, rather than treating manufacturing energy demand as an exogenous parameter.

Case-study evidence. The approach was examined using an automotive exhaust assembly case. Under a traditional specification, a tight global tolerance (± 0.3 mm) is applied broadly, which is associated with staged correction and frequent repositioning. In the function-driven scenario, ± 0.3 mm is maintained for Critical-to-Function (CTF) interfaces while non-critical geometry is relaxed (± 1 – 2 mm). Within the assumptions of the modeled process architecture, this reallocation is associated with fewer stations and reduced annual energy consumption (5 to 3 stations; approximately 250 to 150 MWh/year).

Environmental significance and robustness. The reported reductions are consistent in direction when expressed at different levels of aggregation (per-unit, gate-to-gate metrics and annualized station energy), noting that absolute values depend on the selected system boundary, throughput assumptions, and background electricity emission factors. The sensitivity analysis indicates that the magnitude of CO₂ reduction varies with grid intensity, whereas the reduction in energy demand is less sensitive to the electricity mix. These results suggest that design-stage reductions in energy demand can complement supply-side decarbonization measures.

Implications for practice and future research. The findings motivate a tolerancing workflow in which CTF features are first identified based on interface-driven functional requirements (e.g., mounting points and sealing/connection interfaces), followed by capability assignment and tolerance allocation that preferentially constrains these features. In principle, relaxing non-critical requirements can enlarge the feasible process window and may reduce reliance on intermediate correction operations. Future work should evaluate these steps across a broader set of products and plants, and assess how alternative fixture concepts,

throughput levels, and quality-control strategies moderate the observed energy and emissions outcomes.

Key Findings

- In the examined case, the function-driven scenario reduced the modeled station count from 5 to 3.
- The corresponding annual energy demand decreased from approximately 250 to 150 MWh/year under the stated assumptions.
- Within the scope of the case study, relaxing non-critical geometry while maintaining CTF capability did not indicate functional degradation.
- Reductions in stations and correction operations imply potential CAPEX and OPEX benefits; however, these economic effects are context-dependent and require plant-specific validation.

Final Engineering Principle

Not all geometry deserves the same level of precision.

Overall, SPM provides a structured way to link precision engineering decisions to process design choices and their environmental implications, thereby addressing a frequently cited gap between GD&T practice and sustainability assessment. Further research is warranted to generalize the framework beyond a single component family, incorporate richer functional-performance models, and use more detailed, plant-specific energy inventories.

Notwithstanding these limitations, the results support the view that function-driven precision allocation can represent a scalable lever for reducing manufacturing energy demand without compromising product interfaces that govern functional performance.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Where industrial confidentiality constraints apply, aggregated or anonymized data may be provided.

Competing Interests

The author(s) declare no competing interests.

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Author Contributions

Conceptualization, Methodology, Formal analysis, Investigation, Writing—original draft, Writing—review & editing.

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