Systems Engineering Meets Manufacturing: Optimizing Mining Equipment Assembly via SEEGOL

BUSINESS PROBLEM

Heavy equipment assembly operations face systemic inefficiencies that Lean and Six Sigma tools are structurally ill-suited to resolve. At Caterpillar's Decatur, IL facility, parts handling, retrieval waste, and kitting delays consume a meaningful share of total assembly time across interdependent logistics subsystems. These are not isolated failures but symptoms of a value chain lacking rigorous architectural comparison. No existing framework treats operational systems as combinatorial architecture spaces evaluated against competing performance objectives. A systems-engineering- informed approach is needed.

DATA SOURCES

1. WMS Pick Sheet Logs - warehouse records used for algorithm development

2. Operational Time Studies - floor observations quantifying N-NVA time

3. MVP Controlled Trials - timed tests for concept solutions

4. Post-Deployment LPH Records - picker efficiency metrics

5. Stakeholder Interviews and Gemba Walks - qualitative inputs for requirements and concepts

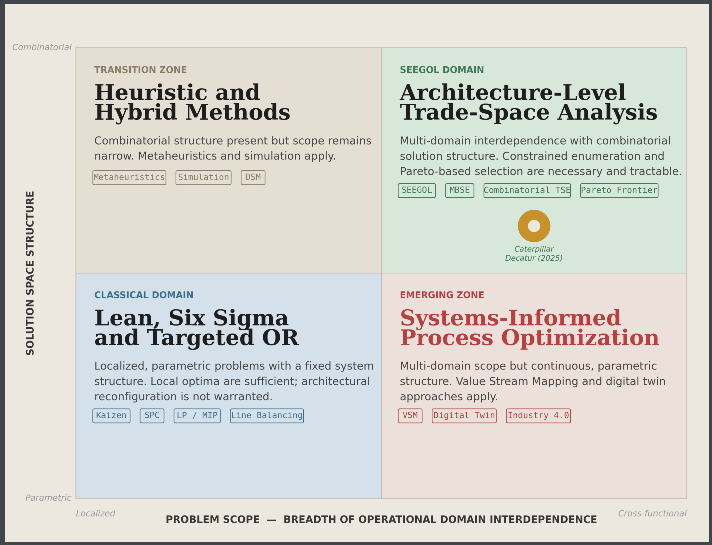
6. Warehouse layout - weighted directed graph

Data Types and Format

Boolean, Graph Structure, Numeric, Structured, Unstructured

APPROACH

This work applies MBSE principles to manufacturing value chain design through a staged pipeline: stakeholder analysis, hierarchical requirements decomposition, combinatorial concept generation, constrained architecture enumeration, and Pareto-based trade-space evaluation. Over 100,000 architectural permutations across 21 solution concepts were assessed against two stakeholder-valued parameters: Additional Throughput and Lifecycle Cost s. Deployed solutions include a TSP- based route optimization algorithm for warehouse logistics, and a Pick-to-Light pilot at the assembly point-of-use.



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IMPACT

SEEGOL (Systems Engineering-Enabled Generalization for Operational Efficiency and Lean) is the primary contribution of this thesis. It is a generalizable MBSE framework that applies systems engineering principles to manufacturing value chain design, filling a gap that Lean, Six Sigma, and conventional OR tools leave unaddressed: the systematic selection of the operational system configuration itself. Rather than optimizing within a fixed system structure, SEEGOL treats the architecture as the primary decision variable, formalizing this upstream selection as an OR-adjacent problem class. The architectural design space is a binary integer feasibility problem; Pareto -based evaluation constitutes a bi-objective optimization on that feasible set. This enables organizations to evaluate combinatorial design spaces and identify near-globally optimal configurations with analytical grounding rather than intuition.

Deployed at Caterpillar's Decatur, IL facility, SEEGOL produced two concrete operational outcomes.

(1) SuperPick, a TSP-based route optimization algorithm embedded in the Warehouse Management System, achieved a 7.9% improvement in warehouse picker efficiency within two weeks of full-scale deployment, converging on its theoretically predicted interval.

(2) The Pick-to-Light pilot at the assembly point-of-use demonstrated an average 45.4% reduction in part-picking time across subjects under controlled MVP conditions, with full-scale deployment underway at time of writing.

Together, these results validate SEEGOL's capacity to deliver measurable operational impact while advancing a replicable, industry-agnostic methodology for architecture-level manufacturing improvement.

DRIVERS

Caterpillar's mining equipment business faces pronounced demand cyclicality. During downturns, throughput improvement and waste reduction become primary margin levers. Existing Lean tools addressed local inefficiencies but lacked a mechanism for architecture-level design across interdependent subsystems, motivating a more rigorous approach.

BARRIERS

Proprietary, facility-specific data limited model fidelity and generalizability. Stakeholder comprehension of MBSE outputs was uneven. WMS integration constraints bounded algorithm design. Change management resistance required careful organizational sequen cing before technical deployment.

ENABLERS

WMS access enabled algorithm development and deployment. A cross -functional Value Chain team provided organizational entry and credibility. Sustained Gemba presence built operator trust and surfaced hidden constraints. MVP prototyping validated assumptions before full investment. SEEGOL's structured review cadence accelerated stakeholder alignment.

ACTIONS

Conducted time studies and Gemba walks to quantify N-NVA inefficiencies. Built a Stakeholder Value Network to formalize requirements. Generated 21 solution concepts across six operational domains. Constructed and filtered a combinatorial architecture space via Constraint Matrix. Validated candidates through MVP trials. Selected and deployed SuperPick and Pick- to-Light via Pareto-based trade-space analysis. Monitored post-deployment performance.

INNOVATION

SEEGOL is the first framework to formally apply MBSE trade-space methodology to manufacturing operational configuration. Rather than optimizing within a fixed structure, it treats architecture as the primary decision variable, casting selection as a binary integer feasibility problem on a Pareto frontier. This bridges a gap between systems engineering and OR, enabling near-globally optimal value chain design vs. intuition-driven local optima.

IMPROVEMENT

SuperPick achieved a 7.9% improvement in warehouse picker efficiency (Lines per Kitter -Hour) within two weeks of full-scale deployment. The Pick-to-Light MVP demonstrated a 45.4% average reduction in assembly part-picking time under controlled conditions. At the architecture level, SEEGOL replaced intuition-driven improvement with a systematic, Pareto-grounded selection process across 100,000+ candidate configurations.

BEST PRACTICES

Sustained Gemba presence is essential, not preliminary. MVP validation should precede full investment. Stakeholder comprehension of trade-space outputs requires deliberate preparation. MBSE overhead is justified when the design space is combinatorial, stak eholder objectives create real trade-offs, and solutions span multiple interdependent domains.

OTHER APPLICATIONS

SEEGOL applies to manufacturing environments where improvements span interdependent subsystems and stakeholder objectives create real trade-offs. Near-term targets include aerospace assembly, defense, and industrial machinery. Longer-term, digital twin integration could evolve it into a persistent decision-support tool using live operational data.