

Multi-Level Hybrid Optimization Model of Value Stream Mapping

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Abstract

Modern manufacturing systems increasingly include parallel production branches, shared resources, and synchronization-dependent assembly operations. Under such conditions, delays generated at specific operations may propagate across multiple production stages and influence overall manufacturing lead time. Conventional Value Stream Mapping (VSM) approaches remain limited in analyzing these interactions because they primarily provide static flow representation and focus mainly on localized waste identification. This research proposes the Hierarchical Governing-Path Optimizing Value Stream Mapping (HGP-OVSM) model to support the analysis and improvement of manufacturing performance in complex production environments. The framework combines hierarchical production representation, process-precedence network analysis, the Critical Path Method (CPM), mixed-integer linear programming (MILP), and multi-objective optimization to evaluate governing-path behavior and operational improvement priorities. The model was implemented computationally using Python and applied to a real manufacturing system consisting of interconnected production lines and synchronization-sensitive assembly stages. The optimization model selected two paths with 37 operations for improvement from 104 processes. The governing-path lead time decreased from 142,409.61 to 103,820.19 seconds, corresponding to a 27.10% reduction, reducing lead time from 1.65 days to 1.20 days, which considers the first path. The second path lead time decreased from 125,887.6 to 93,300.86 seconds, corresponding to a 25.88% reduction, reducing lead time from 1.46 days to 1.07 days. Total non-value-added (NVA) activity decreased from 560,739.51 to 392,517.66 seconds, representing a 30% reduction under process-improvement eligibility constraints associated with implementation feasibility and improvement capacity constraints. In addition, governing-path process-cycle efficiency increased from 9.68% to 13.27%. The results showed that system-level improvement was governed primarily by operations located on dominant production paths rather than by isolated local improvements alone. The analysis further demonstrated that changes in improvement feasibility and optimization priorities may alter governing-path dominance and redistribute bottleneck pressure across interconnected production branches. Overall, the proposed HGP-OVSM framework extends VSM toward optimization-oriented manufacturing analysis capable of supporting improvement prioritization and lead time control within complex multi-path production systems.

Keywords

Manufacturing Optimization, Value Stream Mapping, Critical Path, Bottleneck, Multi-Objective Optimization.

Biographies

Metin Türkay is a Professor and Head of the Department of Industrial Engineering at Koc University, Istanbul, Turkey. He holds a PhD from Carnegie Mellon University (1996) and MS (1991) and BS degrees (1989) from Middle East Technical University. His research focuses on optimizations theory, mixed-integer programming, and development of novel solution algorithms for mixed-integer programming problems and machine learning. He is applying these theoretical developments on energy planning, sustainable energy, sustainable supply chain management and logistics, design of transportation system with special emphasis on sustainable supply chain and logistics and systems biology. Before joining Koc University in 2000 where he set up Systems Lab, he was principal consultant on optimization technologies at Mitsubishi Corporation Mizushima Research Center. His doctoral work and publications on generalized disjunctive programming was recognized with the 1997 Ted Peterson Student Paper Award by Computing and Systems Technology Division of AIChE. He is also the recipient of the Scientific and Technological Research Council of Turkey (TÜBİTAK) Career Award (2005), the TÜBİTAK Young Researcher Incentive Award (2006), Turkey's first IBM Shared University Research Award (2007), the IBM Faculty Award (2009) and the Open Collaborative Research Award by IBM Haifa Research (2012). He set up the Koc-IBM Supply Chain Research Center with funds from the IBM Shared University Research Award. In 2006, he was elected as the Chair of the EURO Working Group on Computational Biology, Bioinformatics and Medicine. Metin Türkay published over 150 papers and is the recipient of 14 international patents.

Ali Abdulhafidh Ali Hasan is a Ph.D. candidate in Industrial Engineering and Operations Management at Koç University, Istanbul, Türkiye, where he serves as a Teaching and Research Assistant. He holds both a B.S. and M.S. in Industrial Engineering from Lebanese International University (LIU), as well as a Technical Bachelor's degree in Energy Engineering, specifically in Heating, Ventilation, Air-conditioning, and Cooling (HVAC), from the General of Technical and Professional Education, Beirut, Lebanon. His academic and research interests focus on lean manufacturing Optimization and technology, value stream mapping, sustainability, quality management systems, and production control technologies. His work also explores the integration of control technologies, sustainability, and quality-oriented decision-making to enhance industrial performance and support green and technological transitions. He gained teaching experience during his work as a teaching assistant in industrial engineering, as well as early academic and technical teaching and training in HVAC. He has practical experience that includes the design and installation of HVAC, central, and commercial cold storage systems, as well as supervising the implementation of electrical plans. He has also prepared feasibility studies for industrial and small-to-medium-sized projects.