ISSN: 1672 - 6553

JOURNAL OF DYNAMICS AND CONTROL

VOLUME 10 ISSUE 02: P50-57

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JOURNAL OF DYNAMICS AND CONTROL

https://doi.org/10.71058/jodac.v10i02004

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Abstract: *Manufacturing lines operating under high demand and constrained resources require systematic load planning to achieve timely delivery and efficient utilization of available capacity. In multi-stage production systems, imbalance between upstream and downstream operations often leads to bottlenecks, excessive Work-in-Process (WIP) inventory, and dependence on overtime. This study presents a computational load planning and capacity analysis of a Two-Wheeler Rocker Arm (TWRA) manufacturing line using actual shop-floor data. Python-based computational programs were developed to evaluate daily and weekly production capacity, identify bottleneck stations, quantify demand gaps, and estimate buffer inventory under different operating scenarios, including normal working hours, demand-gap-based selective overtime, and extended overtime configurations. The results demonstrate that line throughput is governed primarily by downstream bottlenecks rather than total installed capacity and that targeted overtime at critical stations effectively bridges demand gaps. The proposed computational framework provides a transparent and repeatable decision-support tool for capacity planning and continuous improvement in multi-stage manufacturing systems.*

Keywords: *Load Planning; Capacity Analysis; Bottleneck Identification; Overtime Planning; Work-in-Process Inventory; Lean Manufacturing; Computational Decision Support.*

1. Introduction

Modern manufacturing systems are characterized by increasing demand variability, shorter delivery lead times, and rising pressure on operational efficiency. Under such conditions, effective load planning and capacity analysis is essential to ensure that production systems meet customer demand without excessive overtime or uncontrolled inventory growth. In multi-stage manufacturing lines, imbalance between processes often creates bottlenecks that restrict throughput and degrade overall system performance.

Traditional load planning approaches based on manual calculations are time-consuming and unsuitable for repeated evaluation under changing operating conditions. Computational tools provide a structured and repeatable means of analyzing production capacity, identifying constraints, and assessing alternative operating scenarios. Prior studies have established that system throughput is governed by the slowest operation in the line,

https://doi.org/10.71058/jodac.v10i02004

consistent with lean manufacturing principles and the Theory of Constraints (Goldratt, 1990; Womack & Jones, 2003).

This paper presents a computational load planning and capacity analysis of a TWRA manufacturing line. The study focuses on evaluating demand feasibility, identifying bottleneck stages, and analyzing the impact of selective and extended overtime configurations on throughput and buffer inventory. The key contribution of this work lies in translating classical capacity and bottleneck concepts into a practical computational framework that enables repeatable, data-driven evaluation using real shop-floor data.

2. Literature Review

Capacity planning and load balancing are fundamental aspects of manufacturing system design and operation (Stevenson, 2018; Vollmann et al., 2005). Hopp and Spearman (2011) demonstrated that imbalance in processing times leads directly to increased WIP and longer lead times, consistent with Little's Law (Little, 1961). Lean manufacturing emphasizes synchronization of flow and control of bottlenecks to reduce waste and improve responsiveness (Ohno, 1988; Womack & Jones, 2003).

The Theory of Constraints identifies bottleneck resources as the primary determinants of system throughput and advocates focused improvement at constrained stations (Goldratt, 1990; Dettmer, 1997). Overtime is commonly employed as a short-term corrective measure to address demand surges, although prolonged reliance on overtime increases operational cost and workforce fatigue (Slack et al., 2016).

Recent research highlights the growing role of computational and digital decision-support tools in production planning and capacity evaluation (Nahmias & Olsen, 2015; Groover, 2019). Such tools support Industry 4.0 initiatives by enabling data-driven analysis while retaining human judgment in decision-making (Kagermann et al., 2013).

3.0 Description of the Manufacturing System

The TWRA manufacturing line analyzed in this study consists of six major production stages arranged according to the physical flow of material:

1. Soft Machining.
2. Heat Treatment (batch process).
3. Hard Machining.
4. Chrome Coating (batch process).
5. Buffing.
6. Inspection and Packing.

The system operates with three shifts per day. Soft Machining, Hard Machining, Buffing, and Inspection are modeled as hourly-rate processes, while Heat Treatment and Chrome Coating are treated as batch processes that follow the incoming material flow. Actual machine rates, number of machines, and available working hours were used as inputs for the analysis.

4.0 Methodology

A Python-based computational framework was developed to perform load planning and capacity analysis for the TWRA manufacturing line. Daily production capacity for hourly-rate stations was calculated using production rate, available working hours per shift, number of shifts, and machine count. Batch-based stages were modeled using a flow-following assumption, with batch capacity considered sufficient unless identified as a constraint.

https://doi.org/10.71058/jodac.v10i02004

Finished goods output was determined based on the throughput of the final production stage. Bottlenecks were identified by comparing station-wise effective capacities. Demand gaps were quantified, and overtime requirements at constrained stations were computed accordingly. Work-in-process inventory was estimated using a conservative snapshot-based approach to assess buffer accumulation under different operating scenarios. This methodology enables consistent and repeatable evaluation of multiple scenarios without modifying the underlying production data. The detailed computational logic, input parameters, and scenario-wise program outputs used for load planning and capacity analysis are provided in Appendix A.

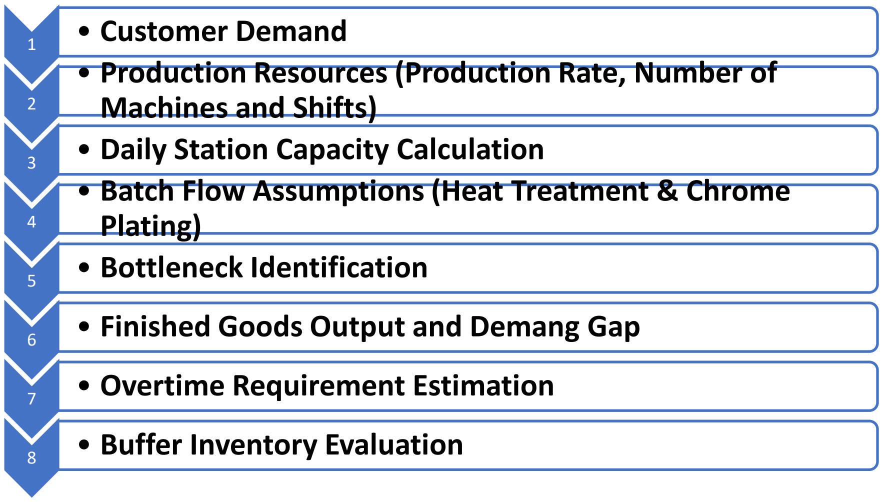

Figure 1. Load Planning and Capacity Analysis Framework

5.0 Load Planning under Normal Working Conditions

Under normal working hours without extended overtime, upstream Soft Machining exhibited higher capacity than downstream Hard Machining, Buffing, and Inspection stages. Consequently, finished goods output remained below the customer demand of 7,500 units per day. Hard Machining was identified as the primary bottleneck restricting overall throughput.

This imbalance resulted in accumulation of WIP upstream of the bottleneck, particularly between Soft Machining and Hard Machining. The findings confirm that increasing upstream output alone does not improve system performance unless downstream constraints are addressed.

6.0 Demand-Gap-Based Selective Overtime Analysis

To address the observed demand gap, a demand-gap-based selective overtime model was applied. The model computed the overtime required at hourly-rate bottleneck stations to achieve a planned output of 2,500 units per shift. The analysis indicated that Hard Machining, Buffing, and Inspection required approximately 0.44 hours of overtime per shift.

Selective overtime improved throughput while avoiding unnecessary overtime at non-bottleneck stations. However, even with selective overtime, finished goods output remained

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marginally below demand, indicating the need for either extended overtime or long-term capacity enhancement.

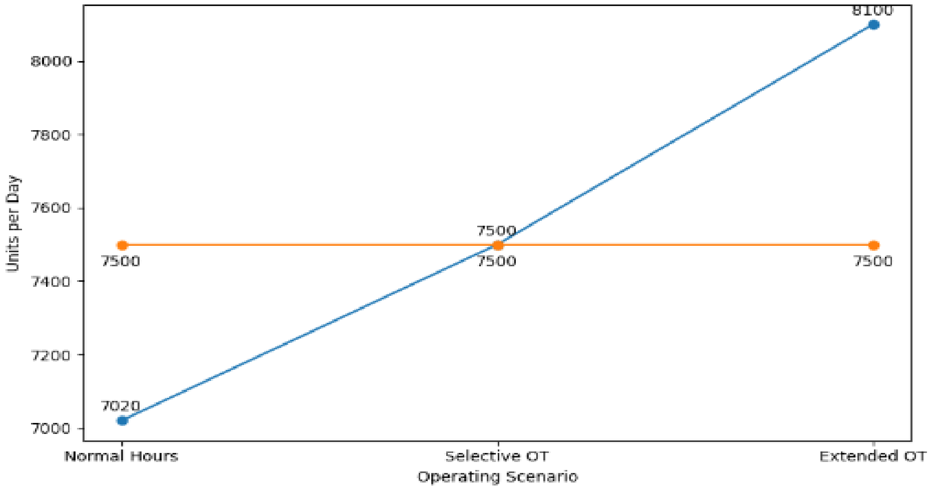

Figure 2. Comparison of Customer Demand and Finished Goods Output under Different Operating Scenarios.

7.0 Extended Overtime and Improved Configuration

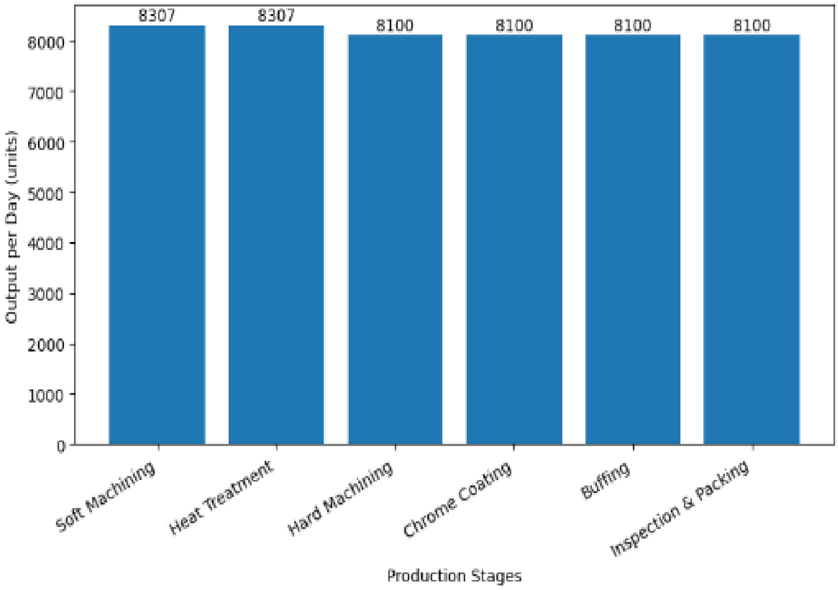

Figure 3. Station-Wise Daily Production Capacity of the TWRA Manufacturing Line under Extended Overtime Configuration.

An extended overtime configuration involving one additional hour per shift at bottleneck stations was evaluated. Under this configuration, finished goods output increased to approximately 8,100 units per day, exceeding customer demand. Batch stages followed the increased flow without becoming constraints, confirming sufficient batch capacity under the assumed operating conditions.

The results demonstrate that targeted overtime at critical stations effectively eliminates the demand gap and creates a controlled production surplus.

https://doi.org/10.71058/jodac.v10i02004

8.0 Buffer Inventory Analysis

Buffer inventory analysis revealed that excess production accumulated primarily at the input of the Hard Machining stage. A daily excess of 207 units resulted in an additional weekly buffer of 1,449 units. While this increased total WIP, the buffer provided operational flexibility by allowing temporary reduction of overtime or absorption of short-term demand fluctuations.

This highlights the trade-off between throughput assurance and inventory holding in capacity planning decisions.

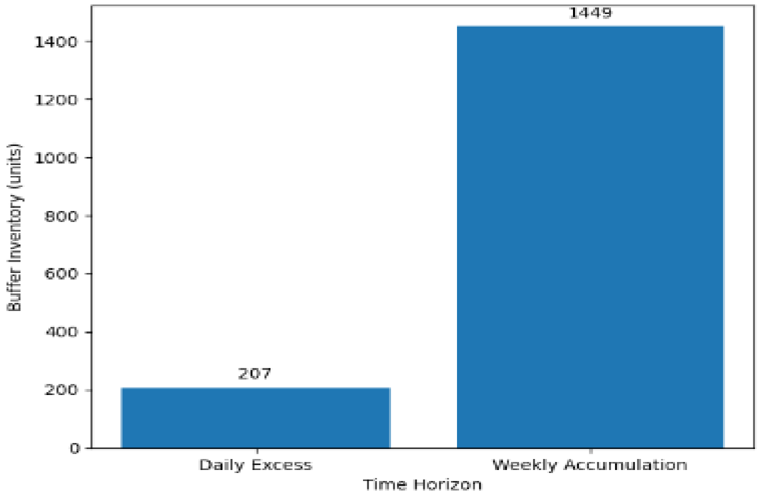

Figure 4. Buffer Inventory Accumulation at the Hard Machining Interface Under Extended Overtime Configuration.

9.0 Results and Discussion

The results confirm that system throughput is governed by downstream bottlenecks rather than total installed capacity. Selective overtime is an effective short-term strategy for meeting demand when applied at constrained stations. However, sustained reliance on overtime increases operational costs and inventory levels, emphasizing the need for long-term improvements such as process optimization or capacity expansion.

The computational framework developed in this study enables transparent evaluation of production scenarios and supports data-driven decision-making without reliance on complex optimization algorithms. The computational evaluation of alternative operating scenarios was carried out using the framework described in Appendix A.

10.0 Conclusions

This study presented a computational load planning and capacity analysis of a TWRA manufacturing line using actual shop-floor data. The key conclusions are:

1. Bottleneck stations significantly restrict throughput under normal operating conditions.

https://doi.org/10.71058/jodac.v10i02004

2. Demand-gap-based selective overtime provides a precise method for capacity improvement.
3. Extended overtime enables full demand satisfaction but increases buffer inventory.
4. Computational decision-support tools provide reliable and repeatable support for continuous improvement initiatives.

The proposed framework can be readily adapted to similar multi-stage manufacturing systems.

11.0 Future Work

Future work may incorporate stochastic factors such as machine breakdowns and processing time variability to assess system robustness (Hopp & Spearman, 2011). Explicit modeling of batch sequencing and queue formation would further enhance realism (Nahmias & Olsen, 2015). Integration of cost-based optimization and real-time data from ERP or Manufacturing Execution Systems would support adaptive load planning aligned with Industry 4.0 initiatives (Kagermann et al., 2013).

"Supplementary computational details supporting the analysis presented in this paper are provided in the Appendix."

Appendix A: Computational Programs for Load Planning and Capacity Analysis

Appendix A.1 Purpose of the Computational Programs

To support the load planning and capacity analysis presented in this study, a set of Python-based computational programs was developed. These programs translate shop-floor production data into quantitative estimates of station-wise capacity, finished goods output, bottleneck identification, demand gaps, and buffer inventory accumulation. The intent of the computational approach is to support decision-making through transparent analysis rather than replace managerial judgment.

Appendix A.2 Input Parameters

The computational programs use actual production data collected from the TWRA manufacturing line. Key input parameters include:

- Customer demand per day.
- Number of shifts per day.
- Available working hours per shift (normal and overtime).
- Station-wise production rates.
- Number of machines at each station.
- Identification of batch-based processes.
- Stations eligible for overtime.

All parameters reflect real operating conditions and remain constant across scenarios, except for changes in working hours related to overtime configurations.

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Appendix A.3 Load Planning under Normal Working Conditions

The first program evaluates production capability under normal working hours. For hourly-rate stations, daily capacity is computed using production rate, working hours, number of shifts, and machine count. Batch processes such as Heat Treatment and Chrome Coating are modeled using a flow-following assumption unless explicitly constrained.

Finished goods output is determined by the throughput of the final production stage, and bottlenecks are identified by comparing station-wise effective capacities.

Appendix A.4 Demand-Gap-Based Selective Overtime Analysis

The second program computes the overtime required at constrained stations to bridge the gap between finished goods output and customer demand. Overtime is distributed only to identify bottleneck stations, ensuring efficient utilization of additional working hours. Revised capacities and outputs are recalculated to assess feasibility.

Appendix A.5 Extended Overtime Configuration

An extended overtime scenario involving one additional hour per shift at bottleneck stations is evaluated. The program recalculates station capacities and finished goods output to assess surplus generation and downstream feasibility.-

Appendix A.6 Buffer Inventory Estimation

Work-in-Process (WIP) inventory is estimated using a snapshot-based method. Excess production upstream of the bottleneck is treated as buffer inventory. Weekly buffer accumulation is calculated by aggregating daily excess quantities over the planning horizon.

Appendix A.7 Program Outputs

The computational programs generate the following outputs:

- Station-wise daily and weekly production capacity.
- Bottleneck identification.
- Finished goods output.
- Demand gaps and overtime requirements.
- Buffer inventory accumulation.

These outputs form the basis for figures and discussions presented in the main paper.

Appendix A.8 Reproducibility and Applicability

The programs are modular and enable rapid re-evaluation under varying demand, shift patterns, or machine configurations. Although developed for a TWRA manufacturing line, the framework is applicable to other multi-stage manufacturing systems. Full program listings are retained to support reproducibility and can be provided upon reasonable request.

Acknowledgments

The author expresses their sincere gratitude to Mr. Antony Raj, Head of Production, and Mrs. Naveen, Assistant Manager, Production Department, Mrs. Vinay N., Quality Analyist for their invaluable support, guidance, and encouragement throughout this research work.

https://doi.org/10.71058/jodac.v10i02004

Funding Statement: No financing/There is no fund received for this article or the authors did not receive financing for the development of this research.

Data Availability: All that support the findings of this study, testing, and trials were conducted within the company's Production, Quality, and SCM departments. The company and component details have been kept confidential in accordance with the confidentiality agreement.

Conflict of Interest: The authors declare that there is no conflict of interest.

Ethical Declarations: This study was conducted using process and production data provided by the participating company. No experiments were performed on humans or animals, and no personal data were collected. Therefore, ethical approval and informed consent were not required for this research.

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