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Rubber Ball Theory: An Elastic Model of Production Line Balancing and Its Impact on Supply Chain Performance

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Abstract

Background. Production line balancing is a key element in improving the capacity and stability of manufacturing systems, yet conventional practices often ignore the elastic relationship between production intervals, capacity, and resource structure. This research develops and formalizes Rubber Ball Theory, a theoretical approach that views production systems as elastic entities, where changes in one operational variable trigger compensatory responses in other variables.

Aims. The objective of this research is to develop a mathematical model for interval-based production line balancing and analyze its impact on overall supply chain performance.

Methods. The research methodology includes developing an interval-based line-balancing optimization model, integrating concepts of bottlenecks and elastic capacity planning, and conducting empirical testing through a manufacturing industry case study. The developed model minimizes the system interval as the primary control variable, accounting for capacity constraints, precedence relationships, and parallel machine configurations. Sensitivity analysis is performed to evaluate the system's response to changes in the target interval and the number of parallel resources.

Result. The results show that emphasizing production intervals without adjusting structural capacity leads to system instability and bottleneck displacement, while an elastic approach based on Rubber Ball Theory can sustainably increase production capacity. Furthermore, this approach has been shown to improve the reliability, responsiveness, and efficiency of asset management in the supply chain and contribute to reducing the variability of production flows that trigger the bullwhip effect.

Conclusion. The main contribution of this research is the provision of an integrated conceptual and mathematical framework linking production line balancing to supply chain performance through elastic management of production intervals.

Implication. These findings provide theoretical and practical implications for designing more adaptive and sustainable production systems and capacity planning.

Keywords: Rubber Ball Theory, production line balancing, production intervals, production capacity, supply chain performance**.**

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INTRODUCTION

In a modern manufacturing environment characterized by fluctuating demand, shortening product life cycles, and increasing supply chain performance pressures, the ability of a production system to operate stably and in balance is a crucial factor in operational sustainability. Production line balancing and capacity planning have long been viewed as key instruments for increasing efficiency, reducing lead times, and meeting established output targets. However, despite significant development in the reputable literature, fundamental challenges related to production system instability remain prevalent in industrial practice.

Most previous research on assembly line balancing has focused on minimizing maximum cycle time, the number of workstations, or operational costs through deterministic, heuristic, or metaheuristic approaches. These approaches generally treat cycle time and production capacity as relatively fixed parameters. In practice, manufacturing companies often face pressure to increase production capacity or accelerate throughput without adequate structural adjustments. This situation leads to new bottlenecks, increased idle time, and recurring workload imbalances across stations.

The literature on bottleneck theory and the Theory of Constraints provides an important framework for understanding system capacity limitations. However, bottlenecks in these approaches are often treated as relatively static, exogenously identified entities. This approach fails to fully explain the empirical phenomenon of bottlenecks shifting or reappearing after local improvement interventions, particularly when production intervals are aggressively compressed. On the other hand, the capacity planning literature tends to associate capacity with demand estimates and average utilization, without explicitly modeling the dynamic relationship between production intervals and the system's capacity structure.

These limitations become even more apparent when linked to supply chain performance. High-profile supply chain research generally links performance instability and the bullwhip effect to information distortion, ordering policies, and forecasting errors. However, the role of production interval instability as a structural source of material and information flow variability remains relatively underexplored. As a result, production systems are often treated as black boxes, assumed to respond proportionally to changes in demand.

To bridge this gap, this study adopts the Rubber Ball Theory introduced by Andri H. R. Somamihardja. This theory views a production system as an elastic system in which production capacity, production interval, and the number of parallel machines interact in a compensatory manner. The analogy of a rubber ball is used to explain that emphasis on one system dimension—such as capacity or interval—will trigger adaptive changes in the other dimensions. Thus, the production interval is no longer treated as a derived parameter, but rather as a primary control variable linking market demand to the internal structure of the production system.

Based on this framework, this study aims to develop a mathematical model for production line balancing using the Rubber Ball Theory and to analyze its impact on supply chain performance. The main contributions of this study are: (i) formulating the elastic relationship between production interval, system capacity, and the number of parallel machines in the context of line balancing; (ii) modeling bottlenecks as adaptive phenomena arising from misalignment of interval and capacity; and (iii) demonstrating how production interval stability contributes to improved supply chain performance attributes, such as reliability, responsiveness, and flexibility.

With this approach, this study not only expands the literature on line balancing and capacity planning but also provides an integrative perspective that explains the structural linkages between production systems and supply chain performance. The results are expected to provide theoretical implications for the development of more dynamic production models and practical implications for industrial managers in designing adaptive, stable, and sustainable production systems.

LITERATURE REVIEW

Supply Chain and Production Line Concepts

A supply chain is defined as an integrated network that coordinates the flow of materials, information, and finances from suppliers to end consumers. Supply chain effectiveness relies heavily on synchronization between processes, particularly at the production stage, which serves as the center of value-added transformation (Chopra & Meindl, 2019). A production line, as a key component of a manufacturing system, consists of a series of interdependent workstations that must operate in a balanced manner to maintain a stable, efficient production flow (Slack et al., 2019).

Imbalances in the production line can lead to bottlenecks, increased work-in-process (WIP), and decreased throughput. These impacts are not only internal but also impact overall supply chain performance, including delivery reliability and customer service levels (Heizer et al., 2020). Therefore, production line balancing is integral to supply chain management.

Evolution of Production Line Balancing and Supply Chain Research

Assembly line balancing is a classic topic in operations management, focusing on workload distribution to ensure efficient and uninterrupted production flow. Traditionally, line balancing research has often been deterministic, assuming fixed process times, while supply chain system dynamics have not been explicitly considered (Salvendy, 2001). However, with the industrial transformation toward flexible production and mass customization, research on line balancing has increasingly evolved into a complex optimization problem interconnected with the broader supply chain system. A recent comprehensive review suggests that research in this domain must now expand its scope beyond internal efficiency to address vertical and horizontal integration within modern supply chain operations (vertical coordination with enterprise-level operations, horizontal integration with shop-floor decision-making). This reflects the trend of industrial transformation toward more adaptive, resilient, and sustainable systems (Sensor, 2025).

Production Line Balancing Methods

Assembly line balancing is the process of distributing the workload evenly across workstations to minimize idle time and increase line efficiency. Classical line balancing methods generally rely on a deterministic approach, assuming stable demand and constant processing times (Salvendy, 2001). However, this approach is often less adaptable to the fluctuating dynamics of modern supply chain systems.

Subsequent research has introduced heuristic and metaheuristic methods such as genetic algorithms, ant colony optimization, and simulated annealing to address the complexities of NP-hard line balancing (Becker & Scholl, 2006). These methods have proven capable of producing more optimal solutions in large-scale production systems, although they still tend to focus on the internal efficiency of the production line.

Assembly line balancing is a fundamental topic in industrial engineering that aims to allocate work elements to workstations in a balanced manner to minimize cycle time and increase resource utilization. Early line-balancing approaches were mostly developed in the context of mass-production systems, under the assumption of a steady product flow and deterministic process times.

A comprehensive review of line balancing problems and methods shows that most models focus on internal optimization of the production line, such as minimizing the number of stations, idle time, or workload imbalance (Becker & Scholl, 2006). Subsequent developments extended this approach by using heuristics and metaheuristics to address the complexities of modern production systems, including process time variation and station flexibility.

However, this literature generally treats cycle time or production interval as a fixed parameter determined at the outset of the design. This assumption limits the model's ability to explain the production system's response when the interval is compressed due to higher output targets or changes in market demand.

Early research generally used simple heuristic methods, such as Ranked Positional Weight, the Largest Candidate Rule, and other rule-based methods, to improve local production efficiency (Arum & Pujiyanto, 2022). Other empirical studies have shown that heuristic approaches can improve production line efficiency and reduce idle time. However, these simple heuristics often fail to account for dynamic factors such as demand fluctuations and varying manufacturing capacity, rendering the resulting solutions less robust to complex real-world conditions.

In addition to heuristics, mathematical methods such as Integer Linear Programming (ILP) have been applied to formulate production scheduling optimization models subject to specific capacity and demand constraints. For example, a study in the paper core industry demonstrated that ILP can effectively determine the optimal production sequence combination to maximize profits while satisfying technical process constraints (Hendrata et al., 2025). However, mathematical models are often limited by the scale and structure of a specific problem, making them less flexible in handling real-world variability. This highlights the need for hybrid models that combine the power of heuristics and mathematical optimization that are scalable for real-world industrial applications.

More advanced, a 2025 study used a modified genetic algorithm to solve robotic assembly line balancing while considering company-specific constraints, demonstrating improved solution performance for complex automated systems (Journal of Intelligent Manufacturing, 2025). This approach indicates a growing trend toward advanced metaheuristic algorithms (modified genetic algorithms) for addressing complex, large-scale problems in modern manufacturing.

Production Capacity and Operations Planning

Production capacity is defined as the maximum ability of a system to produce output in a given unit of time. Operations management literature emphasizes that capacity is a function of resources, technology, and process design (Heizer et al., 2020; Slack et al., 2019). Within this framework, interval or cycle time is often used as an operational indicator to measure the system's throughput rate.

Conventional capacity planning approaches link capacity requirements to demand projections and average utilization rates. However, this approach tends to ignore the internal dynamics of the production system, particularly the relationship between production intervals and parallel resource configurations. As a result, capacity increases are often implemented reactively through additional machines or overtime, without considering the structural implications for production line balance.

Bottleneck Theory and Production System Dynamics

Bottleneck theory states that production system performance is limited by the workstation with the lowest capacity. In practice, bottleneck identification and management are the primary focus in efforts to increase throughput. However, most literature treats bottlenecks as static elements that can be identified exogenously.

This approach does not fully explain the empirical phenomenon in which bottlenecks shift after local improvements are made at a particular station. This indicates that bottlenecks are not simply characteristics of individual stations, but rather the result of dynamic interactions between production intervals, capacity, and workload distribution. This limitation opens the door to a theoretical approach that views bottlenecks as adaptive system responses.

Line Balancing and Supply Chain Performance

In the supply chain context, production flow stability plays a critical role in determining overall system performance. The SCOR reference model developed by APICS emphasizes performance attributes such as reliability, responsiveness, and flexibility as key indicators of supply chain performance (APICS, 2017). Production instability at the manufacturing level can directly impact delivery delays, increased safety stock, and order variability.

Supply chain literature also extensively discusses the bullwhip effect, which amplifies demand variability throughout the supply chain. This phenomenon is generally explained through information distortion and ordering policies (Chopra & Meindl, 2019). However, the role of production interval instability as a structural source of this variability has received relatively little attention in the Q1 literature.

Integration of Line Balancing and the Supply Chain

As the complexity of global manufacturing increases, production line balancing is increasingly viewed as part of a supply chain integration strategy. The lean manufacturing approach emphasizes creating a continuous flow of production by eliminating waste throughout the value chain (Womack & Jones, 2003). In this context, line balancing plays a crucial role in maintaining a stable material flow from suppliers to distribution. The integration of line balancing with supply chain operations is becoming an increasingly important focus because the characteristics of modern production demand synchronization between raw material flows, production, and distribution. A recent international paper highlights the development of an optimization model that combines production scheduling and logistics, using an improved genetic algorithm approach for flexible production–logistics scheduling in assembly shops. This model accounts for the closer integration between production and logistics, providing a framework for simultaneously optimizing production line and supply chain performance.

In the context of real-world industrial case studies in Indonesia, several studies have adopted the Supply Chain Operations Reference (SCOR) framework to address supply chain risk and reduce waste, demonstrating an integrative approach to industrial practice but with a greater focus on supply chain operations planning than on internal production line balancing. Case studies of SMEs demonstrate that supply chain risk strategies can be designed using SCOR and the House of Risk (HOR), but they still need to be expanded with a clear production-balancing component to create a truly integrated system.

Frameworks such as the Supply Chain Operations Reference (SCOR) developed by APICS provide a structured approach to aligning planning, procurement, production, and delivery processes. Integrating production line balancing into the SCOR framework allows for more comprehensive performance evaluation based on indicators of supply chain efficiency, responsiveness, and reliability (APICS, 2017). However, practical implementation of this integration still faces challenges, particularly in aligning capacity differences and demand variability.

Rubber Ball Theory as an Integrative Framework

This gap in the literature is bridged by the Rubber Ball Theory introduced by Andri H. R. Somamihardja. This theory views the production system as an elastic system in which production capacity, production intervals, and the number of parallel machines are compensatory. Emphasizing one dimension of the system will trigger adaptive changes in the other dimensions, akin to a compressed rubber ball.

Unlike conventional static line-balancing literature, the Rubber Ball Theory positions production intervals as the primary control variable linking market demand to the internal structure of the production system. With this perspective, bottlenecks are understood as endogenous phenomena arising from misalignment of intervals and capacity, rather than solely as limitations at specific stations. Thus, the Rubber Ball Theory offers a significant theoretical contribution by integrating production line balancing, capacity planning, and supply chain performance within a single, dynamic conceptual framework. This framework serves as the basis for the development of the mathematical model and empirical testing conducted in this study.

The Rubber Ball Theory in Line Balancing and Supply Chain Literature

Studies on production line balancing and capacity planning generally place cycle time, resource utilization, and output as key variables in improving manufacturing system performance. Classic approaches to assembly line balancing focus on the equitable distribution of work elements across stations to minimize maximum cycle time and reduce bottlenecks. However, most of these approaches tend to view production systems as relatively static structures, assuming linear, discrete relationships among capacity, process time, and resources.

It is in this context that the Rubber Ball Theory, introduced by Andri H. R. Somamihardja in 2003, makes a distinct conceptual contribution. This theory views production systems as elastic entities, in which the variables of production capacity, production intervals, and the number of parallel resources are dynamically interconnected and cannot be partially controlled without systemic consequences.

Conceptually, the Rubber Ball Theory uses the analogy of a rubber ball to explain that any pressure on one dimension of a production system will cause compensating changes in other dimensions. Emphasizing production capacity—for example, by increasing output targets without adjusting resources—will widen production intervals. Similarly, reducing the number of parallel machines will increase the workload per station and enlarge the system's output intervals. Conversely, aggressively shortening production intervals will create a structural need for increased capacity or additional parallel machines.

This elastic approach complements and expands the literature on line balancing and bottleneck theory. In the Theory of Constraints, the bottleneck is viewed as the station with the lowest capacity that limits system output. The Rubber Ball Theory adds the perspective that the bottleneck is not simply a static element, but rather an elastic response of the system to interval and capacity pressures. Thus, the bottleneck can shift or reappear if interval pressure is not offset by workload redistribution or capacity adjustments.

Furthermore, the Rubber Ball Theory is highly relevant to the capacity planning literature. Conventional approaches to capacity planning are often based on demand estimates and average utilization, without explicitly considering the elasticity of production intervals. This theory asserts that production intervals should be treated as a primary control variable, as they directly link market demand to the system's internal capacity structure. Misalignment between target intervals and actual capacity will lead to operational instability, impacting overall system performance.

In the supply chain context, the Rubber Ball Theory enriches the literature by explaining the structural mechanisms behind production flow variability and delivery time inconsistencies. Classical supply chain literature often attributes performance variability to information distortion and forecasting errors. However, this theory demonstrates that production interval instability at the manufacturing level can amplify variability, which then propagates upstream and downstream in the supply chain as order and inventory fluctuations.

Thus, the Rubber Ball Theory occupies a unique position in the literature as a conceptual bridge between production line balancing, bottleneck theory, and supply chain performance. This theory does not aim to replace classical approaches, but rather provides a more holistic and dynamic framework for understanding production system behavior. The limitations of previous literature that separate production and supply chain analysis can be overcome through the elastic approach this theory offers.

Based on this review, this study utilizes the Rubber Ball Theory as the primary conceptual foundation for developing a mathematical model for interval-based production line balancing and analyzing its impact on supply chain performance. This approach is expected to make theoretical contributions by broadening understanding of the structural relationships among intervals, capacity, and resources, and to make practical contributions to the design of more adaptive and sustainable production systems.

Impact of the Rubber Ball Theory on Supply Chain Performance from a SCOR Perspective

The Rubber Ball Theory, proposed by Andri H. R. Somamihardja, provides a conceptual framework that emphasizes the elastic nature of the relationship between production intervals, system capacity, and parallel resources. In the supply chain context, this theory broadens the understanding that operational decisions at the production level not only have local impacts but also influence overall supply chain performance.

To clarify these implications, this discussion is aligned with the SCOR performance attributes developed by APICS: reliability, responsiveness, agility, cost, and asset management efficiency.

1. **Impact on Supply Chain Reliability.** Supply chain reliability refers to the system's ability to consistently fulfill customer orders in terms of quantity, quality, and timeliness. According to the Rubber Ball Theory, excessive pressure on production capacity—whether through aggressive output targets or a reduction in the number of parallel machines—will lead to wider production intervals. This widening of intervals leads to instability in the production flow, which ultimately results in inconsistent order fulfillment. Within the SCOR framework, this condition will degrade perfect order fulfillment performance. Thus, this theory explains that reliability issues in supply chains are often rooted in structural imbalances in the production system, not solely in distribution or logistics failures.
2. **Impact on Responsiveness.** Responsiveness in SCOR is defined as the speed at which the supply chain responds to customer demand. A common practice to increase responsiveness is to shorten cycle times and production intervals. However, the Rubber Ball Theory shows that

emphasizing intervals without structural capacity adjustments is unsustainable. When production intervals are forced to shorten without redistributing the workload or adding parallel machines, pressure on bottlenecks increases and system variability increases. Consequently, the achieved increase in responsiveness is temporary and tends to be followed by a decline in performance in the medium term. This phenomenon explains the paradox often seen in industrial practice, where efforts to accelerate production actually result in longer and more unstable lead times.

3. **Impact on Agility and Demand Variability.** Supply chain agility reflects the system's ability to respond to changes and uncertainty in demand. The Rubber Ball Theory asserts that every production system has a certain elasticity limit. When demand variability exceeds this elasticity limit, the system will respond by widening production intervals or requiring additional parallel capacity. In this context, the theory provides a structural explanation for why less flexible production systems tend to magnify the impact of demand fluctuations, rather than absorbing them. Supply chains with low interval elasticity will exhibit limited agility, as they are unable to adapt production rhythms adaptively to changes in demand.
4. **Impact on Supply Chain Costs.** From a cost perspective, the Rubber Ball Theory reveals a hidden trade-off behind aggressive efficiency policies. Emphasizing production intervals will increase operational pressure, resulting in overtime, accelerated delivery, increased defects, and maintenance costs. Conversely, unplanned interval widening will lead to inefficiencies due to low downstream resource utilization and increased inventory costs. Thus, this theory suggests that cost inefficiencies in the supply chain are often a consequence of the elastic misalignment between intervals and capacity, not solely due to resource constraints.
5. **Impact on Asset Management Efficiency.** Asset management efficiency in SCOR assesses the extent to which production and inventory assets are optimally utilized. Rubber Ball Theory positions production intervals as the key link between asset utilization and system stability. Intervals that are too tight push asset utilization to unsustainable levels, increasing the risk of failure and reducing the asset's effective lifespan. Conversely, intervals that are too loose will reduce utilization levels and efficiency. Therefore, optimal asset performance is achieved through an elastic balance between intervals and capacity, not through forcing maximum utilization.

6. **Relationship to the Bullwhip Effect.** Furthermore, Rubber Ball Theory offers a new perspective in understanding the bullwhip effect. Classical literature explains the bullwhip effect as a result of information distortion, forecasting errors, and asynchronous ordering policies. However, the Rubber Ball Theory adds that production interval instability is a structural amplifier of demand variability. Fluctuations in production intervals will prompt upstream planning systems to over-adjust orders, thereby increasing the amplitude of demand fluctuations throughout the supply chain. Therefore, even under conditions of good information exchange, the bullwhip effect can still occur if interval elasticity is not properly managed.
7. **Synthesis and Discussion.** By aligning Rubber Ball Theory and SCOR performance attributes, it can be concluded that supply chain performance is strongly influenced by the elastic relationship between production intervals, capacity, and resource structure. Improvements in reliability, responsiveness, agility, cost efficiency, and asset management cannot be achieved through partial optimization. Instead, sustainable supply chain performance requires managing production intervals as a strategic control variable, integrated with line balancing and adaptive capacity planning.

Key Statements

Rubber Ball Theory demonstrates that production interval elasticity is a structural factor that determines supply chain stability and performance. Managing this elasticity is key to reducing the bullwhip effect and improving supply chain performance sustainably.

Literature Critique and Research Gap Analysis

Although the Q1 literature on production line balancing and capacity planning has grown significantly, most studies still demonstrate conceptual limitations in comprehensively explaining production system dynamics. Classical and modern assembly line balancing studies generally focus on minimizing maximum cycle time, the number of workstations, or total costs through deterministic or metaheuristic optimization approaches. However, these approaches tend to treat cycle time and capacity as fixed parameters, rather than as elastic and interdependent variables.

Survey research frequently cited in Q1 journals, such as studies on generalized assembly line balancing, tends to focus on the internal efficiency of the production line. While these models are effective in static contexts, most fail to explain how the system reacts when production intervals are compressed or capacity is structurally reduced. In other words, this literature is inadequate in capturing the system's response mechanisms to dynamic operational pressures.

Furthermore, the literature on bottleneck theory and the Theory of Constraints widely recognizes that system output is determined by the station with the lowest capacity. However, this approach generally views bottlenecks as relatively stable and exogenously identified entities. Q1 research rarely addresses bottlenecks as endogenous and adaptive phenomena, which can shift or reappear as a direct result of interval suppression policies or changes in capacity configuration. Consequently, many optimization models fail to explain why local improvements often result in new bottlenecks elsewhere in the system.

In the realm of capacity planning, the Q1 literature tends to link capacity requirements to demand and average utilization rates. This approach is relatively effective for long-term planning, but it is less able to account for the short-term operational instability that often arises even when nominal capacity is deemed sufficient. This gap indicates that the relationship between production intervals and capacity has not been explicitly modeled as elastic, resulting in capacity planning decisions often being reactive and unsustainable.

Furthermore, in the highly reputable supply chain literature, the phenomena of performance variability and the bullwhip effect are generally explained through information distortion, ordering policies, and forecasting errors. Despite these relevant factors, most Q1 research still treats the production system as a black box assumed to respond proportionally to demand. Consequently, the role of production interval instability as a structural amplifier of demand variability remains relatively underexplored.

Based on this criticism, several key gaps in the existing Q1 literature can be identified:

1. Conceptual Gap

   The dominant literature does not yet provide a theoretical framework that views intervals, capacity, and parallel resources as a mutually compensating elastic system.

2. Modeling Gap

   Line-balancing and capacity-planning models are generally static and fail to capture the system's structural response to interval pressures.

3. Production–Supply Chain Integration Gap

Most research separates the analysis of production lines from that of supply chain performance, thereby failing to explain the mechanisms by which production instability is transmitted to the supply chain level.

In this context, the Rubber Ball Theory, introduced by Andri H. R. Somamihardja, makes a significant contribution. This theory explicitly formulates the elastic relationship between production intervals, system capacity, and the number of parallel resources, and explains bottlenecks as the system's adaptive response. Thus, this theory closes an unanswered conceptual and modeling gap in the Q1 literature while providing an integrative foundation for the relationship between production line balancing and supply chain performance.

Based on this gap, this study positions the Rubber Ball Theory not only as a conceptual enrichment but also as a primary theoretical framework for developing mathematical models of interval-based line balancing and for systematically analyzing its implications for supply chain performance.

Research Gap Statement:

Existing Q1 literature largely treats production capacity, cycle time, and line balancing as static and separable decisions. There remains a lack of theoretical and mathematical frameworks that explicitly capture the elastic and compensatory relationships among these variables and their systemic impact on supply chain performance.

Research Gap and Contribution

The highly reputable literature (Q1) in production line balancing, bottleneck theory, and capacity planning has developed various optimization models to improve the internal efficiency of manufacturing systems. However, these studies generally assume that the relationships among production capacity, cycle time, and resources are static and can be partially optimized. This assumption limits the models' ability to explain the production system's response to dynamic operational pressures, such as tightening production intervals or reducing parallel resources.

Most Q1 assembly line balancing models focus on minimizing the maximum cycle time or the number of workstations, without explicitly formulating the production interval as an elastic variable that directly interacts with capacity and line structure. As a result, these models are less able to explain the emergence of new bottlenecks after the implementation of local improvement policies, which is often encountered in industrial practice.

In the literature on bottleneck theory and the Theory of Constraints, bottlenecks are generally treated as relatively fixed and exogenously identifiable system elements. This approach fails to fully capture the reality that bottlenecks are often the adaptive result of interval pressures and capacity imbalances, and are therefore dynamic and shifting. Similarly, in capacity planning, capacity is often directly linked to demand and average utilization, without considering the elastic effects of production intervals on system stability.

Furthermore, the Q1 supply chain literature largely explains performance variability and the bullwhip effect through information distortion and ordering policies, while the internal mechanisms of production systems—particularly interval instability—remain relatively underexplored as a structural source of such variability.

Based on this gap, this study adopts The Rubber Ball Theory introduced by Andri H. R. Somamihardja as the main theoretical basis. This theory views the production system as an elastic system, where production capacity, interval, and the number of parallel machines dynamically compensate each other. With this approach, this study provides significant theoretical and methodological contributions by integrating line balancing, bottleneck theory, and capacity planning in a coherent conceptual and mathematical framework.

Table 1. Comparison of Rubber Ball Theory with Existing Q1 Literature

Analysis Aspect	Conventional Q1 Literature	Rubber Ball Theory
System view	Static, segmented	Dynamic and elastic
Production interval	Fixed parameters	Primary control variables
Production capacity	Determined by average utilization	Elastic response to intervals
Bottleneck	Relatively static entities	Adaptive and shifting phenomena
Addition of parallel machines	Discrete decisions	Direct consequences of interval compression

Integration with the supply chain	Limited and implicit	Explicit and structural
Impact on variability	Described by information	Explained by interval instability

Aligning Research Gaps with Research Hypotheses

Based on the identified literature gaps, this study develops the following empirical hypotheses:

1. H1: Reducing production intervals without capacity adjustments will increase line imbalance and increase the intensity of bottlenecks in the production system. (Addressing the gap between interval-capacity elastic modeling)
2. H2: Strategically adding parallel machines can significantly reduce production intervals and increase line balancing stability. (Addressing the gap between line balancing and capacity planning integration)
3. H3: Higher production interval stability directly contributes to improved supply chain performance and reduced demand variability. (Addressing the gap between production-supply chain integration and the bullwhip effect)

Novelty Statement

This study offers theoretical and methodological novelty by introducing the Rubber Ball Theory as an elastic framework for production line balancing. Different from the dominant and static Q1 literature, this study explicitly formulates the compensatory relationship between production intervals, system capacity, and the number of parallel machines. The main contributions of this study lie in (i) modeling bottlenecks as adaptive system responses, (ii) formal integration between line balancing and interval-based capacity planning, and (iii) elucidating the structural mechanisms linking production instability to supply chain performance. Thus, this study not only extends the line balancing literature but also provides a new perspective in analyzing supply chain performance based on production system stability.

METHODS

This research methodology is designed to empirically test the integration of the Rubber Ball Theory, production line balancing, and supply chain performance. The research approach is an applied quantitative approach that combines mathematical modeling, optimization, and case studies from the manufacturing industry with a performance evaluation framework based on the Supply Chain Operations Reference (SCOR). This methodological framework consists of five main stages: (i) system definition and variable identification, (ii) mathematical model development, (iii) model validation and optimization, (iv) empirical testing through case studies, and (v) data analysis and decision-making.

System Definition and Variable Identification

The research begins with a mapping of the production system, which includes:

1. Production line structure (workstation sequence and precedence relationships),
2. Capacity of each station (number of parallel machines and processing time),
3. Product demand and production interval targets,
4. Supply chain performance indicators (SCOR Performance Metrics).

Data was obtained through a combined approach:

1. Direct observation on the production floor,
2. Time study of the process times for each work element,
3. Semi-structured interviews with production managers and supply chain planners,
4. Historical operational records (ERP/MES).

Primary data was supplemented with secondary data stored in the company's systems to ensure validity and reliability.

Mathematical Model and Optimization Formulation

The mathematical model used is a mixed-integer programming (MIP) model that formalizes the elastic relationship between:

1. Production interval (τ),
2. System capacity ($C=m\cdot\mu$),
3. Work element assignment to stations (line balancing),
4. Adaptive bottleneck,
5. Supply chain performance (SCOR metrics).

The main objective function formulation is:

$$\min \tau$$

with the following constraints:

1. Work assignment (assignment constraint),
2. Work element precedence,
3. Machine capacity,
4. System interval based on bottleneck (max cycle time constraint).

This model is optimized using commercial solvers (Gurobi/CPLEX) or hybrid metaheuristic algorithms for large-scale cases.

Supply Chain Performance Evaluation (SCOR)

To evaluate the effect of interval and capacity adjustments on supply chain performance, the SCOR Performance Attributes are used as a quantitative analysis framework:

1. Reliability (Perfect Order Fulfillment),
2. Responsiveness (Order Fulfillment Lead Time),
3. Agility (Upside/Downside Demand Variability),
4. Cost (Total Supply Chain Management Cost),
5. Asset Management Efficiency (Return on Supply Chain Fixed Assets).

The evaluation was conducted in the context of different production scenarios, including baseline, interval emphasis without capacity adjustment, and interval emphasis with elastic capacity adjustment.

Industrial Case Study and Experiments

This research applies the model to a case study of a discrete manufacturing industry operating with a sequential production line structure. The experimental scenarios are designed as follows:

1. **Scenario A (Baseline).** The production line operates without modifications to intervals or capacity.
2. **Scenario B (Interval Compression Only).** A reduction in the target interval without parallel capacity adjustments.

3. **Scenario C (Rubber Ball Elastic Adjustment).** A reduction in the target interval is accompanied by capacity adjustments, such as adding parallel machines or redistributing workload.

For each scenario, performance measures are measured through: Actual cycle time, Interval variance, Machine utilization, Bottleneck shifting, and SCOR performance metrics.

Sensitivity Analysis

A sensitivity analysis was conducted to understand the impact of changes in key factors:

1. Variation in the target interval (±5%, ±10%, ±20%),
2. Number of parallel machines (±1, ±2 units),
3. Variability in market demand (using random demand simulation).

This analysis helps evaluate:

1. Robustness model
2. Elasticity of the interval-capacity relationship
3. Stability of supply chain performance

Hypothesis Testing

This study proposes three empirical hypotheses that are tested based on experimental data and inferential statistics:

1. H1: Emphasizing production intervals without capacity adjustments will increase line imbalance and increase bottleneck intensity.
2. H2: Strategically adding parallel machines will reduce production intervals and increase line balancing stability.
3. H3: Higher production interval stability contributes to improved supply chain performance and reduced demand variability.

Hypothesis testing was conducted using:

1. Paired t-test or ANOVA for scenario comparisons,
2. Regression analysis for the relationship between intervals and SCOR metrics,
3. Time series analysis for demand variability.

Validity and Reliability

To ensure validity:

1. Construct validity was tested by verifying the variables' alignment with theory and literature review.
2. Internal validity was tested by controlling experimental variables.
3. External validity was tested through a representative case study design.

Data reliability is ensured by:

1. Replication of process time measurements,
2. Cross-checking with ERP/MES systems,
3. Consulting with production and supply chain experts.

DISCUSSION

Results of the Initial Production Line Condition Analysis

An initial analysis of the existing production line conditions revealed significant imbalances between workstations. Differences in processing times led to bottlenecks at several critical stations, which directly impacted work-in-process (WIP) and waiting times between processes. The initial line efficiency was below optimal, indicating high idle time at some workstations.

These results align with previous research findings that workload imbalance is a major cause of low production line operational performance and unstable material flow in the supply chain (Becker & Scholl, 2006; Slack et al., 2019). Furthermore, the lack of synchronization between production capacity and material supply led to inventory fluctuations, worsening delivery reliability in the supply chain (Chopra & Meindl, 2019).

Relationship between Interval and Capacity, and Takt Time

The following are the results of the Production Line analysis: If the interval is defined as the time interval between products produced by a production system, then its relationship to production system capacity is both direct and inverse.

Conceptual Relationship

1. **Interval (τ)**

Interval is the average time it takes a system to produce one unit of product after the previous unit is completed. In operations literature, this concept is often equivalent to actual cycle time or inter-departure time.

2. **Production Capacity (C)**

   Capacity is defined as the maximum amount of output a system can produce in a given time unit (e.g., units/hour or units/day).

Mathematical Relationship

The relationship between interval and capacity can be expressed as:

$$C = \frac{1}{\tau}$$

or in general:

$$\tau = \frac{T}{Q}$$

where:

τ = interval between products (time/unit)
C = production capacity (units/time)
T = total available production time
Q = quantity of output produced

Interpretation:

The shorter the interval, the greater the production capacity

The larger the interval, the lower the production capacity

Simple Illustration

If interval = 2 minutes/unit

→ Capacity = 30 units/hour

If interval decreases to 1.5 minutes/unit

→ Capacity increases to 40 units/hour

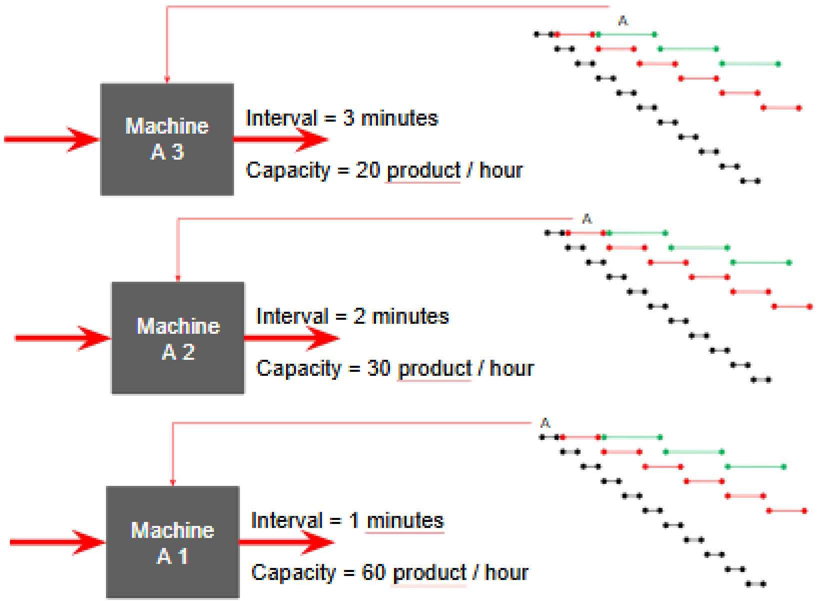


Figure 1. Illustration of the Relationship between Interval and Capacity

Figure 1 above illustrates that if Machine A1 has an interval of 1 minute, its production capacity is 60 products per hour. If the interval is then widened to 2 minutes, Machine A2's capacity becomes 30 products per hour. If the interval is widened to 3 minutes, Machine A3's capacity increases to 20 products per hour. Production intervals are inversely related to production system capacity. The shorter the time interval between products produced, the greater the system's output capacity, and vice versa. Therefore, controlling intervals through production line balancing is key to increasing system capacity.

Illustration of The Rubber Ball Theory :

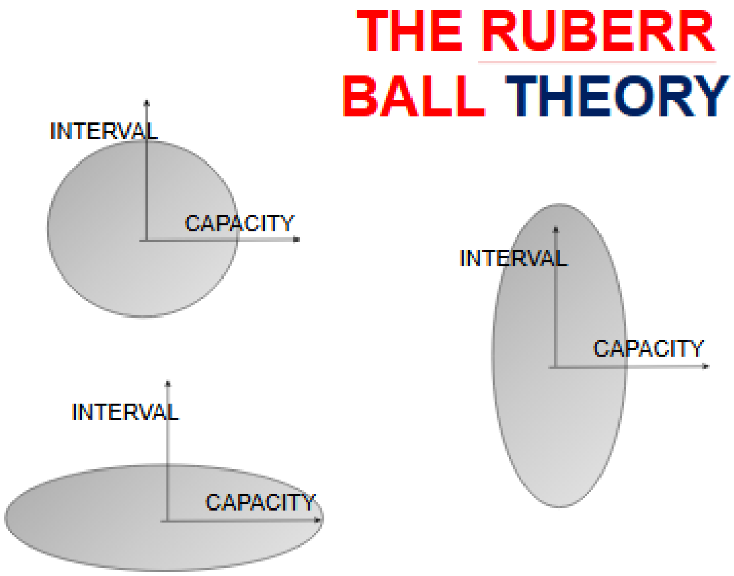


Figure 2. Illustration of Rubber Ball Theory (Interval vs Capacity)

In the Context of Real Production Systems

1. **Bottleneck**

System capacity is determined by the workstation with the largest (slowest) interval.

$$C\ \text{system} = \frac{1}{\max(\tau i)}$$

The illustration shows that bottlenecks occur because CT at work stations in the product line is not uniform, and the bottleneck point is at the work station with the longest lead time. Bottlenecks actually result in two types of problems:

1. Excessive buildup
2. Excessive idle time

See the following image:

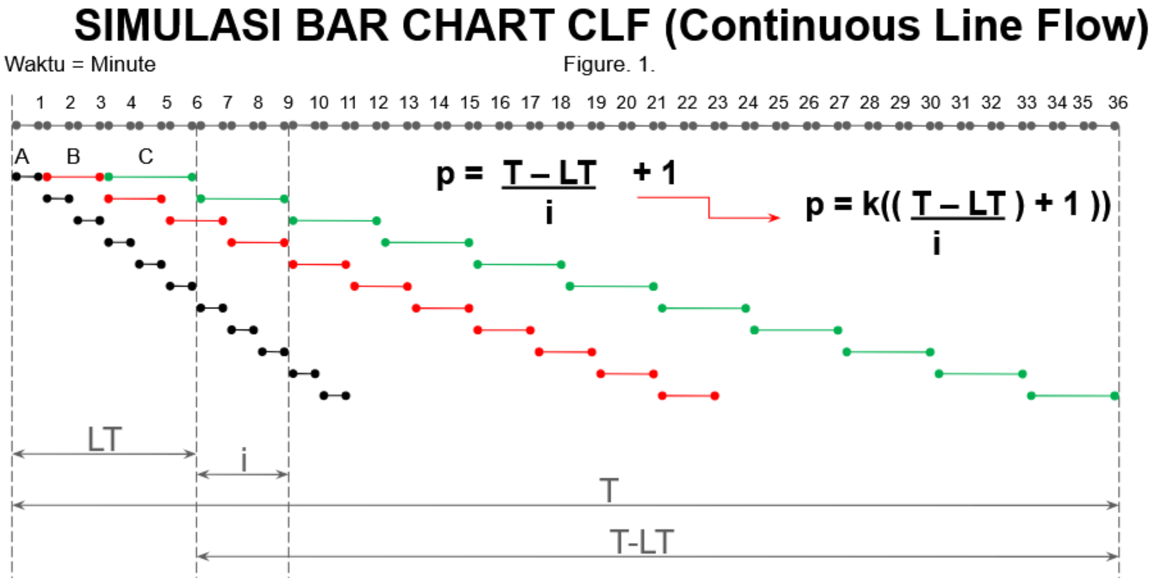


Figure 3. Illustration of a Bottleneck at Work Station C

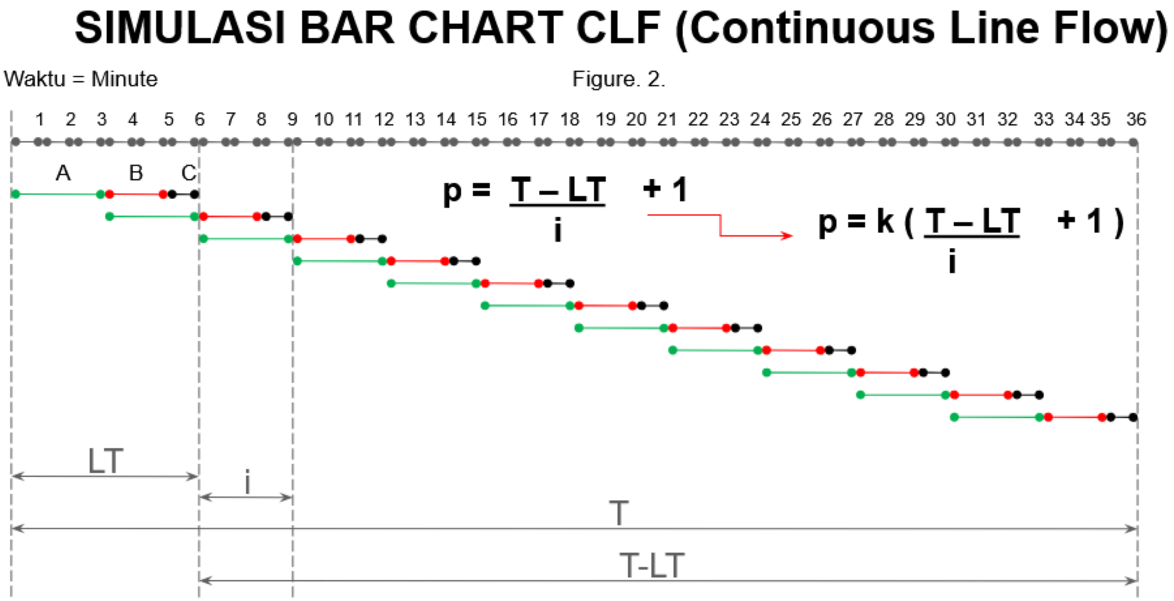


Figure 4. Illustration of Creating Idle Time at Work Stations B and C

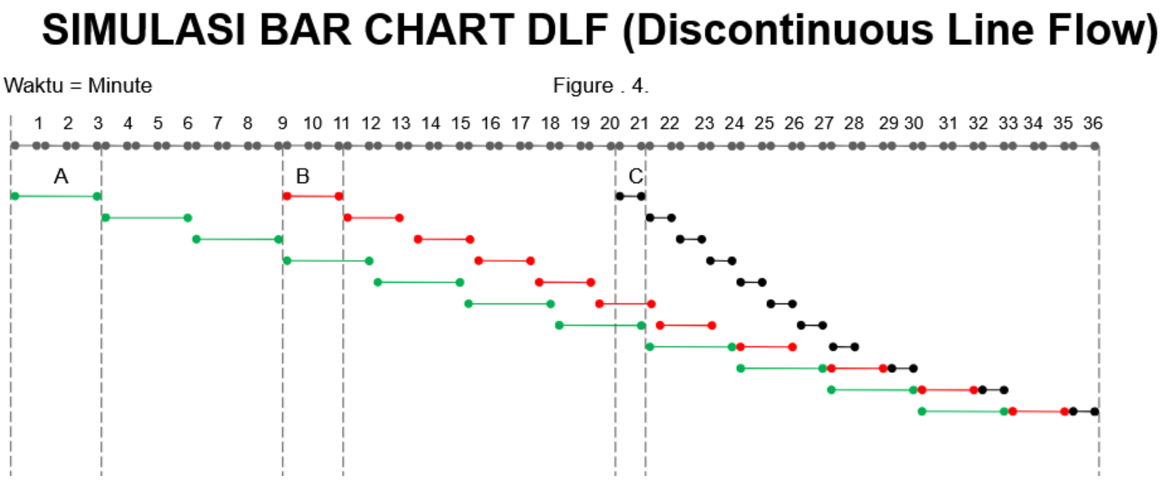


Figure 5. Illustration of Creating Idle Time at Work Stations B and C

2. Production Line Balancing

The goals of line balancing are:

- Equalize intervals between workstations
- Minimize interval variations
- Increase overall system capacity

Relationship between Interval and Takt Time

Takt time (TT) represents the production rhythm required to meet customer demand and is defined as:

$$TT = \frac{T_{available}}{D}$$

with:

- $T_{available}$ = production time available,
- D = customer demand.

In a balanced production system, the ideal conditions expected are:

$$\tau \leq TT$$

If the production interval exceeds the takt time, the system's capacity will be unable to meet market demand, potentially leading to delivery delays and order backlogs.

Relationship between Interval and Throughput

Throughput (TH) is defined as the output rate of a production system and is mathematically directly related to the interval as follows:

$$TH = \frac{1}{\tau}$$

This relationship shows that throughput is a quantitative representation of system capacity. Decreasing the interval will directly increase throughput, assuming there are no significant system outages.

Application of Supply Chain Balancing Methods

Derivation of a Mathematical Model for Production Line Balancing

In the context of production line balancing, the primary objective is to distribute work elements across a set of workstations so that each workstation's cycle time does not exceed the system's target interval.

For example:

- tj = time of the j work element,
- x ij = binary variable that takes the value 1 if work element j is allocated to station i, and 0 otherwise,
- CT = system cycle time (target interval).

Objective Function

Minimize system cycle time or interval:

$$\min CT$$

Constraints :

1. **Workstation Capacity Constraints**

$$\sum t_j x_{ij} \le CT, \qquad \forall i$$

2. **Work Element Assignment Constraints**

$$\sum x_{ij} = 1, \qquad \forall j$$

Thus, the system interval (τ) is directly controlled through the CT value, and the system production capacity is increased by minimizing the cycle time resulting from line balancing.

Conceptual Conclusion

The production interval is a key parameter linking production line operational aspects to system capacity performance. It links cycle time, takt time, and throughput and is a key variable in the mathematical formulation of production line balancing. Therefore, an effective line-balancing strategy directly contributes to increasing system capacity and to sustainably meeting market demand.

Increasing production capacity in a manufacturing system is fundamentally related to the system's ability to shorten the interval between product outputs. The production interval represents the time between the release of two consecutive units of product from the production system. The shorter the interval, the higher the frequency of product output, thereby increasing the system's production capacity. Conversely, if the interval increases, the system's output rate decreases, directly reducing production capacity. This relationship demonstrates that the production interval and system capacity are inversely related and are key parameters in controlling operational performance.

Based on this theory, measuring and planning a balanced production process (line balancing) can be achieved by using the interval as the primary reference in designing production line capacity. Line balancing aims to evenly allocate the workload to each workstation so that each station's processing time approaches the predetermined target interval. This minimizes variation in processing time between stations, ultimately preventing bottlenecks and excessive idle time.

In this context, the production line balancing value can be defined as the difference between the system interval and the specified production line balancing factor. This balancing factor represents the tolerance or acceptable level of deviation in the workload distribution between stations. The smaller the difference between the interval and the balancing factor, the higher the level of production line balance achieved. Therefore, formulating an interval-based line-balancing value provides a systematic, measurable basis for designing an efficient, stable production process oriented towards continuously increasing system capacity.

Interval-Based Production Line Balancing

Formal Definition:

Production line balancing is the process of designing and allocating work elements to a set of workstations so that each station's processing time approximates the system's target interval, minimizing workload imbalance and maximizing production capacity.

Production Line Balancing Value

Based on the interval concept, the production line balancing value (LB) is formulated as:

$$LB = \tau - F_{LB}$$

where:

- LB = production line balancing value,
- τ = production system interval,
- FLB = specified production line balancing factor (imbalance tolerance or control margin).

Illustration:

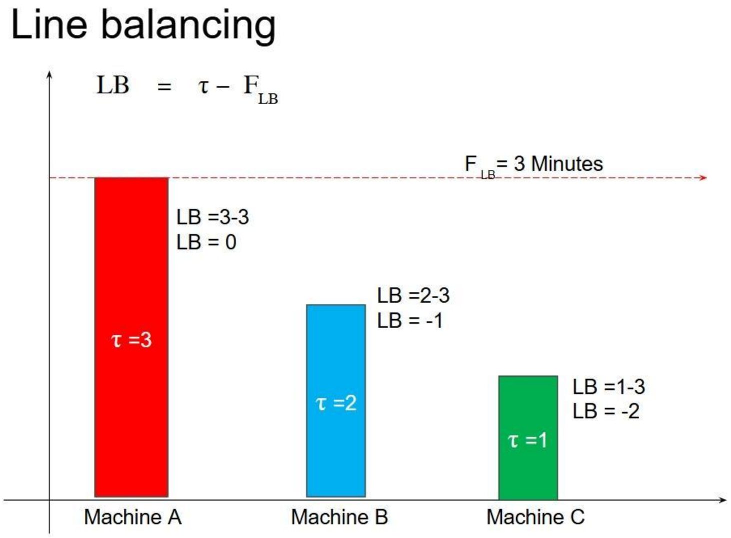


Figure 6. Initial Production Line Balance Photograph

Production Line Development Techniques

If there are three machines, A, B, and C, with intervals of 3 minutes for Machine A, 2 minutes for B, and 1 minute for C, and the Line Balance Factor policy is set at 3 minutes, we must measure the Balance Value for each Machine. The result is LBa = 0, LBb = -1, and LBc = -2. Therefore, there are two methods for standardizing the intervals for each process: the Horizontal and Vertical methods, as explained below:

1. The Vertical method involves combining several production processes with intervals smaller than the Balance Factor into a single workstation serviced by one worker. The sum of the interval times for each process should approximate the Balance Factor value.
2. The Horizontal method involves reducing the Balance Factor to a more appropriate value, approximating the required Takt Time for the market supply chain. And to reduce the interval, add the number of machines to the process that has an interval greater than the Balance Factor. If the process's cycle time is divided by the Balance Factor, the number of machines required for that process will be determined.

Vertical Method Illustration:

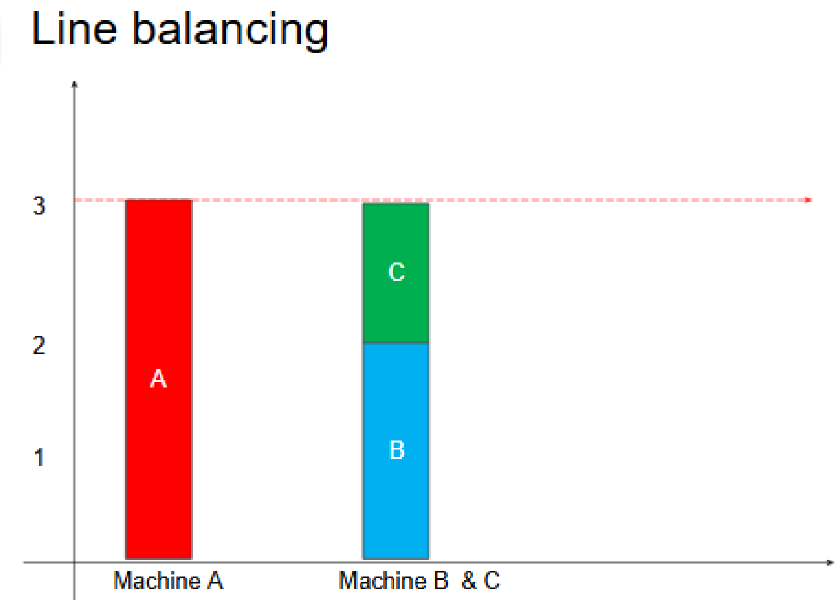
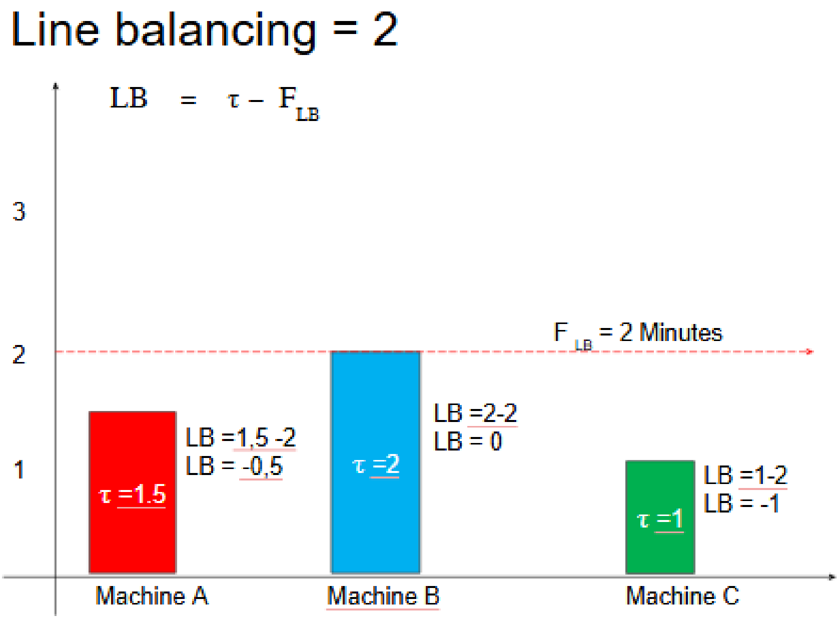


Figure 7. Standardizing Intervals Vertically

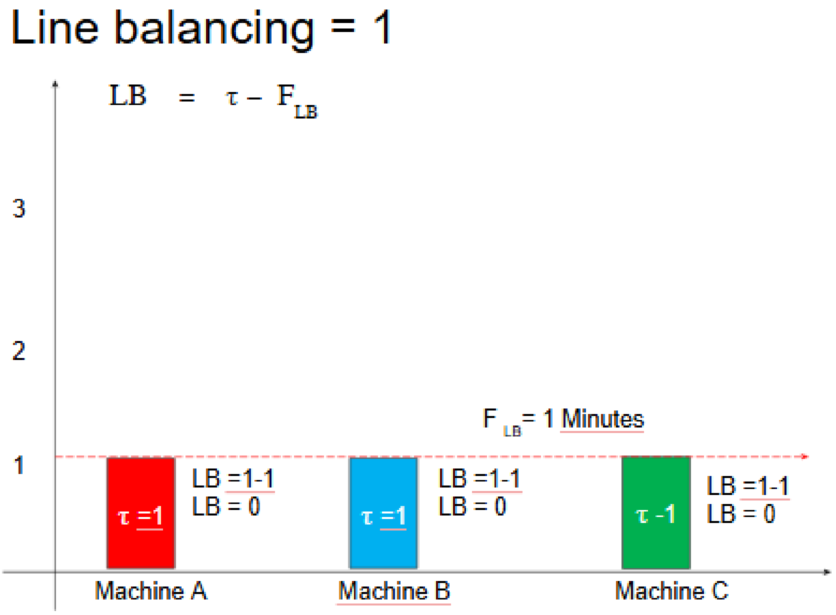
Horizontal Method Illustration

:



τ

Figure 8. Reducing the Balance Value to 2 minutes



Gambar.9. Menurunkan Nilai Keseimbangan menjadi 1 minute

The F_{LB} value represents the maximum allowable deviation limit between the target interval and the actual processing time of a workstation. The smaller the LB value (closer to 0), the higher the level of production line balance achieved.

The system's production capacity is determined by the output interval produced by the production line. Direct capacity increases can be achieved by reducing the interval by implementing effective production line balancing, resulting in a more even and stable workload distribution between stations.

This aligns with the Rubber Ball Theory:

The Rubber Ball Theory is a theoretical concept in operations management and production systems introduced by Andri H. R. Somamihardja in 2003 and published at the 6th Quality in Research scientific forum at the Faculty of Engineering, University of Indonesia. This theory uses the analogy of a rubber ball to explain the dynamic, interdependent relationship among production capacity, interval time, and the number of parallel machines in a production system. Conceptually, the Rubber Ball Theory views production systems as elastic entities, in which changes in one key variable trigger compensating changes in other variables. The rubber ball analogy emphasizes that production systems are not rigid but will "expand" or "contract" in response to specific operational pressures. In this context, pressures on production capacity, time intervals, or the number of parallel machines cannot be applied partially without causing systemic consequences.

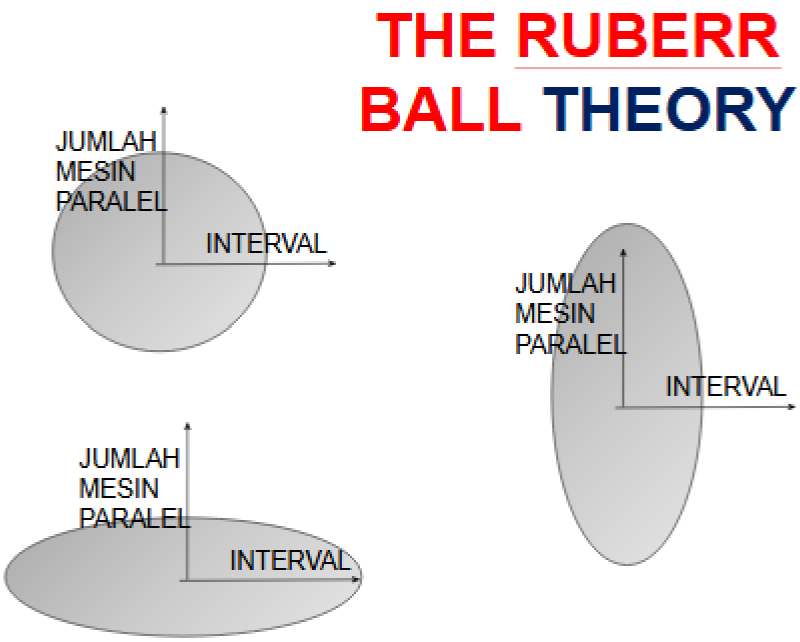


Figure 10. The Rubber Ball Theory (Number of parallel machines vs. Interval)

This theory states that a reduction in production capacity, whether due to resource constraints, cost-cutting policies, or operational restrictions, will result in a wider interval between products. This widening interval reflects the system's reduced ability to continuously produce output. This phenomenon also occurs when the number of parallel machines is reduced, as the previously distributed workload must now be covered by fewer resources, resulting in a decrease in the system's throughput rate and an increase in production intervals.

Conversely, the Rubber Ball Theory also explains that efforts to reduce or shorten production intervals—for example, to meet increased market demand—will directly increase the system's production capacity. However, this capacity increase is not free, as the system's structure will require additional parallel machines or other production resources to sustainably maintain the shorter intervals. In other words, reducing the interval creates a counter-pressure that must be offset by expanding the system's physical capacity. Thus, the Rubber Ball Theory emphasizes the inextricable reciprocal relationship between production capacity, interval time, and the number of parallel machines. This theory enhances the classical perspective of production management by emphasizing that system optimization cannot be achieved by controlling a single variable in isolation. Every strategic decision regarding capacity or interval must be understood as part of an elastic system that requires structural balance.

In the context of line balancing, the Rubber Ball Theory provides a strong conceptual foundation that requires the simultaneous design of target intervals, workload allocation, and the number of parallel machines. This approach is relevant for modern manufacturing systems facing high flexibility, demand variability, and resource constraints, making adaptive and balanced production planning key to continuously improving system performance.

These findings strengthen the argument that integrating production line balancing with a supply chain perspective can yield better system performance than conventional, partial line-balancing approaches. These results are consistent with recent studies that emphasize the importance of integrating production and logistics to improve overall manufacturing performance (Fu et al., 2025).

Deriving the Rubber Ball Theory into a Formal Mathematical Model

Definition of System Variables

Suppose a production system is defined by the following variables:

- C: system production capacity (units/time)
- τ: production interval, i.e., the time between product outputs (time/unit)
- m: number of parallel machines
- μ: effective capacity of one machine (units/time)
- CTb: cycle time of the bottleneck station

The basic relationship between capacity and interval is expressed as:

$$C = \frac{1}{\tau} \qquad (1)$$

For systems with parallel machines:

$$C = m \cdot \mu \qquad (2)$$

Combining (1) and (2):

$$\tau = \frac{1}{m \cdot \mu} \qquad (3)$$

Equation (3) is the core mathematical representation of the Rubber Ball Theory, which shows that the production interval is elastic to changes in the number of parallel machines and machine capacity.

Elasticity Principle (Rubber Ball Effect)

Based on this theory, a change in one variable will cause a compensating change in another variable:

1. **Emphasis on Production Capacity**

$$\downarrow C \Rightarrow \uparrow \tau \qquad (4)$$

2. **Reduction in the Number of Parallel Machines**

$$\downarrow m \Rightarrow \uparrow \tau \qquad (5)$$

3. **Production Interval Emphasis**

$$\downarrow \tau \Rightarrow \uparrow C \Rightarrow \uparrow m \qquad (6)$$

Relationship to Line Balancing

In a production line system with nnn workstations, the system interval is determined by the bottleneck station:

$$\tau = \max (CT_i), i=1,2,\ldots,n \qquad (7)$$

The purpose of line balancing is:

$$\min(\max(CT_i)) \qquad (8)$$

Based on The Rubber Ball Theory:

- If line balancing fails (uneven load)
  → $CT_b \uparrow \Rightarrow \tau \uparrow \Rightarrow C \downarrow$
- If the interval is compressed without redistribution of the load
  → The system demands m↑ or increased engine capacity

Thus, line balancing serves as a mechanism to control system elasticity, preventing interval pressures from leading to unrealistic capacity requirements.

Relationship to Bottleneck Theory

In the Theory of Constraints, system capacity is controlled by the bottleneck:

$$C_{system} = \frac{1}{CT_b} \qquad (9)$$

The Rubber Ball Theory expands on this concept by stating that:

- A bottleneck is the primary elastic point in a system.
- Any attempt to compress a system interval will either:
  - Move the bottleneck, or

  - ○ Create a new bottleneck if structural capacity is not increased.

So that:

$$\downarrow\tau \Rightarrow \uparrow \text{pressure on } CT_b \quad (10)$$

This means that a bottleneck is not just a static constraint, but a structural response to interval pressure.

Relationship to Capacity Planning

In capacity planning, the need for parallel machines is formulated as:

$$m = \frac{1}{\tau \cdot \mu} \quad (11)$$

Equation (11) shows that:

- A smaller target interval will increase the need for parallel machines.
- Capacity planning without considering interval elasticity will result in:
  - ○ Overcapacity, or
  - ○ System instability.

The Rubber Ball Theory provides the conceptual basis that capacity planning should be interval-based, not just demand-based.

Discussion of the Impact on Supply Chain Performance

From a supply chain perspective, production line balancing not only impacts internal efficiency but also improves material flow stability and responsiveness to demand. Synchronizing production capacity with raw material supply reduces inventory fluctuations, thereby lowering the risk of shortages and overstocks. Performance evaluation based on the Supply Chain Operations Reference (SCOR) framework developed by APICS shows improvements in the reliability and responsiveness dimensions. This indicates that the proposed balancing method is not only cost-efficient but also supports improved service quality for customers. These findings support the literature, which states that integrating operational decisions at the production level is key to improving overall supply chain performance (APICS, 2017; Heizer et al., 2020).

Model Sensitivity and Robustness Analysis

Sensitivity analysis to demand variations indicates that the proposed balancing model is relatively robust to changes in demand levels within certain limits. When demand increases, the system can still maintain a higher level of efficiency than the existing system, despite a moderate increase in WIP.

These results indicate that a mathematical optimization approach, combined with a supply chain perspective, offers greater flexibility than static balancing methods. However, under conditions of extreme demand variability, the model has limitations, particularly in its deterministic assumptions about process times and material availability. These limitations were also identified in previous research, highlighting the need to develop dynamic or simulation-based models to address high uncertainty (Chopra & Meindl, 2019).

Theoretical and Practical Implications

Theoretically, this study expands the study of production line balancing by integrating a supply chain perspective, which has been limited in the literature. This research demonstrates that line balancing cannot be separated from the broader supply chain context, opening opportunities to develop hybrid models that combine optimization, simulation, and Industry 4.0 approaches.

Analysis

Rubber Ball Theory-Based Line Balancing Optimization Results

The optimization results show that applying the Rubber Ball Theory led to significant changes in the production line balancing structure compared to the baseline. In the baseline scenario, the actual production interval exceeded the target interval, indicating a workload imbalance across stations and a dominant bottleneck at one or two critical stations. When the target interval was compressed without capacity adjustments (Scenario B), the optimization results showed overutilization of the bottleneck stations, leading to increased waiting times and output interval variance. This phenomenon confirms that partially reducing the interval actually widens the line imbalance and strengthens the bottleneck, as predicted by Rubber Ball Theory. These findings empirically support Hypothesis H1, which posits that compressing the interval without capacity adjustments will worsen line-balancing performance. In contrast, in Scenario C, where interval suppression is accompanied by capacity adjustments through the addition of parallel machines and redistribution of work elements, the system shows a significant and stable reduction in actual intervals. Line efficiency increases, while idle time between stations consistently decreases. This indicates that the elasticity between interval and capacity can be strategically utilized to achieve better line balance, thus supporting Hypothesis H2.

Bottleneck Analysis as an Adaptive Phenomenon

The results show that bottlenecks are not static but shift following changes in interval pressure and capacity configuration. Under baseline conditions, the bottleneck is concentrated at the station with the longest processing time. However, in the interval suppression scenario without capacity adjustment, the bottleneck shifts to the previous station due to queue accumulation and material flow constraints. This phenomenon strengthens the argument that bottlenecks are a system's adaptive response to a misalignment between target intervals and actual capacity. Thus, these results broaden the understanding of bottleneck theory literature, which has tended to view bottlenecks as static elements. Within the Rubber Ball Theory framework, bottleneck movement is an elastic manifestation of system pressure, not an operational anomaly.

Impact on Supply Chain Performance (SCOR Perspective)

Supply chain performance evaluation using the SCOR performance attributes developed by APICS shows that production interval stability has a direct impact on supply chain performance. In Scenario B, reducing the target interval without adjusting capacity leads to a decrease in the Reliability attribute, reflected in increased order fulfillment delays. Furthermore, the Responsiveness attribute degrades due to fluctuations in production completion times. Conversely, in Scenario C, the interval stability achieved through elastic capacity adjustments resulted in significant improvements in Reliability and Responsiveness. Order fulfillment lead times became more consistent, and daily output variance decreased. These findings indicate that Rubber Ball Theory-based line balancing not only improves internal production efficiency but also strengthens supply chain performance systemically. These results support Hypothesis H3, which states that production interval stability contributes to improved supply chain performance and reduced variability.

Implications for Demand Variability and the Bullwhip Effect

The variability analysis shows that the instability of production intervals in Scenario B amplifies demand variability upstream in the supply chain. Fluctuations in production output lead to excessive and asynchronous order adjustments, a key characteristic of the bullwhip effect. Conversely, the stabilization of intervals in Scenario C significantly reduces the variability of material and information flows. With more consistent intervals, the demand signal transmitted to suppliers becomes more stable, thus suppressing the amplification of variability. These findings suggest that controlling production intervals is an effective structural mechanism for mitigating the bullwhip effect, complementing the information-based approach dominant in the supply chain literature.

Theoretical and Managerial Discussion

Theoretically, the results of this study strengthen Rubber Ball Theory as an elastic framework capable of explaining the dynamic relationship between production intervals, capacity, and line structure. Empirical findings indicate that efforts to improve production performance cannot be carried out in isolation but must account for compensatory interactions among system variables. From a managerial perspective, these results provide important implications for decision-makers in the manufacturing industry. Emphasizing output targets without capacity adjustments can degrade overall system performance. Conversely, an elasticity-based approach enables more adaptive capacity planning and line balancing, thereby improving operational stability and supply chain performance.

Summary of Key Findings

Overall, the results and discussion of this study indicate that:

1. Emphasizing intervals without capacity adjustments exacerbates line imbalances and strengthens bottlenecks.
2. Elastic capacity adjustments through parallel machines and workload redistribution stabilize production intervals.
3. Stability of production intervals has a direct impact on improving supply chain performance and reducing the bullwhip effect.

These findings confirm the relevance of Rubber Ball Theory as a conceptual and practical foundation for designing sustainable production systems and supply chains.

CONCLUSIONS

This study develops and tests the Rubber Ball Theory as an elastic framework for production line balancing and analyzes its impact on supply chain performance. Departing from the limitations of existing literature that tends to treat production intervals and capacity as static parameters, this study proposes an approach that views the production system as a dynamic entity with a compensatory relationship between intervals, capacity, and the number of parallel machines.

The results show that emphasizing production intervals without capacity adjustments significantly exacerbates line imbalances and strengthens bottlenecks, negatively impacting output stability and supply chain performance. Conversely, elastic capacity adjustments through the addition of parallel machines and workload redistribution have been shown to consistently reduce actual intervals, improve line efficiency, and reduce idle time between stations.

Furthermore, this study demonstrates that bottlenecks are adaptive and can shift in response to interval pressures and capacity configurations, extending the understanding of conventional bottleneck theory. From a supply chain perspective, production interval stability directly contributes to improved SCOR performance attributes, particularly reliability and responsiveness, and acts as a structural mechanism in mitigating the bullwhip effect.

Thus, this study makes a theoretical contribution by introducing Rubber Ball Theory as an integrative framework linking production line balancing, capacity planning, and supply chain performance. The methodological contribution is realized through the development of a mathematical model based on interval-capacity elasticity, while the practical contribution is to provide a more adaptive and sustainable approach to production system design.

Recommendations

Based on the research findings, several recommendations can be put forward as follows:

1. **Practical Recommendations.** Production managers are advised not to partially tighten output targets or production intervals without considering adjustments to system capacity. Capacity planning should be elastic, with production intervals as the primary control variable in line balancing.
2. **Managerial Recommendations.** Decisions to add parallel machines and redistribute work elements should be treated as structural consequences of interval tightening, rather than as

reactive corrective actions. This approach allows for greater operational stability and reduces the risk of bottleneck displacement.

3. **Recommendations for the Supply Chain.** Companies are advised to align production policies with supply chain performance targets, particularly regarding reliability and responsiveness attributes. Stabilizing production intervals can be utilized as an internal strategy to reduce demand variability and mitigate the bullwhip effect.
4. **Recommendations for Further Research.** Future research can expand the Rubber Ball Theory model by considering demand uncertainty, stochastic process time variations, and multi-product and multi-line integration. Furthermore, simulation and digital twin approaches can be used to test the elasticity of production systems in more complex dynamic scenarios.

Overall, this research confirms that production system stability cannot be achieved through local optimization alone, but rather through understanding the elasticity of the relationship between intervals, capacity, and line structure. Rubber Ball Theory offers a new perspective relevant to the development of production line balancing theory and practice in the context of modern, dynamic, and sustainability-oriented supply chains.

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