Proceedings of the 2025 Winter Simulation Conference
E. Azar, A. Djanatliev, A. Harper, C. Kogler, V. Ramamohan, A. Anagnostou, and S. J. E. Taylor, eds.

APPLYING OPERATING CURVE PRINCIPLES TO NON-MANUFACTURING PROCESSES TO GAIN EFFICIENCY AND EFFECTIVENESS IN GLOBAL SEMICONDUCTOR SUPPLY CHAINS

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ABSTRACT

In today's volatile and complex world, non-manufacturing processes are crucial for global agile and, thus, resilient semiconductor supply chains. Examples of non-manufacturing processes include new product samples, fab overarching process flows, and enabling processes. This conceptual paper begins with the hypothesis that operating curve principles from manufacturing can also be applied to non- manufacturing processes. To achieve this, we needed to understand why the principles of operating curves and flow factors lead to efficiency and effectiveness in semiconductor manufacturing. Our goal was to determine how these principles can be applied to broader contexts and specific use cases. The initial experimental results are promising. Furthermore, it is essential to assess how non-manufacturing processes are structured. The paper concludes with examples demonstrating the potential to bridge the efficiency gap between manufacturing and non-manufacturing processes. The ultimate goal is to match both efficiency levels, thus opening new opportunities within global semiconductor supply chains.

1 INTRODUCTION

In today's increasingly volatile and complex global economy, the semiconductor industry stands out as one of the most technologically demanding and capital-intensive sectors (Mönch, Fowler, and Mason 2013). It is a crucial enabler of innovation in various other industries, such as the automotive sector. To remain competitive, this industry must navigate rapid technological advancements, changing demand patterns, and geopolitical challenges. As a result, developing highly efficient and resilient supply chains is crucial to maintaining competitiveness (Ehm, Ponsignon, and Kaufmann 2011).

Manufacturing processes have been extensively improved by using Operating Curve management (Fayed and Weber 2008). A growing share of non-manufacturing processes that support overall value creation today takes place beyond the factory floor. Non-manufacturing global supply chain processes, while critical to responsiveness, speed, and cost control, remain comparatively understudied and lack systematic approaches for performance optimization. This conceptual paper proposes that the principles of OC management based on factory physics laws (Hopp and Spearman 2011; Hackman and Leachman 1989), developed for manufacturing, can serve as a foundational model for understanding, assessing and improving the performance of non-manufacturing operations, opening new frontiers in global semiconductor supply chains.

1.1 Relevance of Efficiency (and Effectiveness) in the Global Semiconductor Supply Chain

In manufacturing, efficiency and effectiveness are critical because they directly impact cost, quality, and throughput (Liker 2004). The lean for complex-flow production principles (Wikipedia 2024) ensure that the 4Ms: machine, human, material, and method (Schmielau and Bisslich 2024) are optimally used with minimal waste. Effectiveness means achieving the desired goals and ensuring that the output meets the customer's requirements in terms of quality, quantity, and timing. Efficiency, on the other hand, refers to doing things in the best possible way, minimizing resources, time, and effort while maintaining quality (Liker 2004). In this paper, we focus on increasing the efficiency of non-manufacturing processes.

Although non-manufacturing environments are less tangible, efficiency and effectiveness are becoming just as essential, especially in the context of speed and cost of global semiconductor supply chains (Hopp and Spearman 2011). Poor efficiency leads to wasted time and therefore inconsistent results (Porter 1996). For example, inefficient communication or decision-making processes can result in unclear priorities, duplication of efforts, and delays. Ineffectiveness shows up as failed time management or failure to meet internal and external expectations.

Our domain environment is characterized by volatility, uncertainty, complexity, and ambiguity (VUCA) (Frady 2024; Tsujimura 2020) which means that semiconductor companies are compelled to evolve in response to ever-changing customer demands and their customer's needs; therefore, more flexibility and more global supply chains are needed, and as a consequence non-manufacturing processes gain more importance. Despite localization efforts to date, supply chains have become increasingly globalized, and effective work sharing, such as with SiFo (silicon foundries), OSAT (outsourced assembly test), and even borderless fabrication approaches (Herding and Mönch 2023), has continued. We can deduce that non-manufacturing processes in the global supply chain have further increased in importance.

We further conclude that non-manufacturing processes are becoming new key drivers of competitiveness, innovation, and resilience in global semiconductor supply chains. They are likely to gain even more importance with the growing worldwide competition (Miller 2022).

1.2 Applying Operating Curve Principles beyond the Factory Floor

The central thesis of this paper asserts that the foundational concepts of the OC, Little's law (Hopp and Spearman 2011), and flow time principles (Macchi 2008) can be effectively applied to enhance non-manufacturing efficiency. The OC framework offers an invaluable starting point for tackling the challenges faced in non-manufacturing workflows. By adapting these principles, this paper seeks to connect structured manufacturing systems with non-manufacturing processes. This connection highlights the need to extend Little's law and incorporate OCs into new domains. Furthermore, this paper establishes a conceptual foundation for a future research agenda aimed at empirically testing and refining the applicability of OCs, including Little's law, in non-manufacturing environments.

1.3 Research Questions

We formulate the following research questions to guide theoretical and practical investigation:

a. Where is The Need for Improvement in Efficiency and Effectivity of Non-Manufacturing Processes in Global Semiconductor Supply Chains?

There is a need to increase the efficiency and effectiveness of global non-manufacturing processes. Identifying inefficiencies and ineffectiveness in non-manufacturing supply chain processes is crucial, as these issues directly impact speed, cost, and overall supply chain performance.

The methodology applied describes non-manufacturing processes using BPMN (Business Process Model and Notation) with swim lanes and measuring the flow factor (definition provided in Section 2). If this flow factor is significantly higher than what is typically observed in manufacturing, ranging between 3 and 5, we can conclude that there is potential for improved efficiency (defined as doing things the right way). Furthermore, if the process changes more frequently than it does in manufacturing, we can infer that there is potential for improved effectiveness (defined as doing the right thing).

b. What Role does 'the huMan' play in Global Non-Manufacturing Semiconductor Supply Chain Processes?

The ’human’plays a significantly more dominant role in global non-manufacturing semiconductor supply chain processes compared to manufacturing processes. We propose that the transition from machine to human in the 4M methodology is the most important differentiator between manufacturing and non-manufacturing processes (though this still needs to be verified and validated). It is essential to consider how this shift influences the development of more efficient and effective processes.

c. How can the Efficiency and Effectivity be Improved for these Processes?

For efficiency: OC principles, including Little’s law, can be effectively applied to non-manufacturing processes within the global semiconductor supply chain. A structured implementation of Little’s law, flow time principles, and operating curve principles will help minimize inefficiencies in non-manufacturing workflows. This approach emphasizes the importance of identifying and reducing process variability, which is essential for achieving success.

For effectiveness: If it is indeed true that excessive changes in non-manufacturing processes result in ineffectiveness, particularly at the human level, then the primary challenge is to create a practical adaptation of these principles that emphasizes the human factor.

By addressing these research questions, this paper aims to provide initial insights into improving non-manufacturing processes in global semiconductor supply chains and bridging the expected efficiency and effectiveness gap between manufacturing- and non-manufacturing processes.

2 COMPARING MANUFACTURING AND NON-MANUFACTURING WORKFLOWS THROUGH OPERATING CURVES

To effectively manage overall complexity, it is essential to have a conceptual understanding of how variability, load, and prioritization interact in non-physical workflows. We begin this conceptualization by defining how OC principles have been applied within fabs and how they could potentially be applied in non-manufacturing processes outside or between fabs.

2.1 Manufacturing Processes and Their Function

Manufacturing processes are utilized by companies to produce physical goods, such as semiconductors in our case. These processes are defined as a series of steps and operations that transform raw materials, components, or semi-finished products into finished goods (Guevara 2024). They play a crucial role in various industries, including automotive, electronics, aerospace, and semiconductors. When organized efficiently, these processes ensure the production of goods that meet specific requirements and standards, often referred to as ’lean manufacturing’ (Liker 2004).

Lean manufacturing, also known as lean production, originated from the Toyota production system in Japan during the mid-20th century (Becker 1998). This system focused on eliminating waste and maximizing efficiency in manufacturing operations. Consequently, the term ’lean’ became associated with continuous improvement methodologies and practices developed in manufacturing contexts (Liker 2004).

Lean manufacturing emphasizes the identification and elimination of any activity or resource that does not directly contribute to creating value for the customer. This includes reducing waste from excess inventory, unnecessary movement of materials or people, defects, overproduction, and waiting times. Using waste reduction strategies, manufacturing processes aim to minimize waste, improve efficiency, and reduce costs (Liker 2004).

The general principles of lean have been adapted for lean in complex flow production for semiconductor manufacturing (Wikipedia 2024), where recurring process flows create a complex network. With more than 1,000 process steps required for a single wafer, production times can be lengthy, even with fabs operating 365/24 and incurring high capital costs, often exceeding 5 billion dollars for a fully equipped facility. OC management has proven to be effective in managing this complexity (Fayed and Weber 2008; Meier and Nyhuis 2009).

2.2 Successful Operating Curve Principles in Semiconductor Manufacturing

The semiconductor industry faces a significant challenge in balancing two conflicting objectives: the need to quickly bring products to market and the need to maximize manufacturing utilization for cost-effectiveness (Missbauer and Uzsoy 2020). This contrast creates a delicate trade-off between speed, known as flow time efficiency or flow factor (FF), and cost efficiency, which is largely influenced by capital costs associated with utilization.

To optimize the use of their expensive equipment, semiconductor manufacturers require advanced production schedules. Effective OC management is essential to achieve high utilization while maintaining a low FF, thus minimizing time losses and their financial repercussions. In operations management, OC management, including the application of Little's law, serves as a crucial tool for understanding and optimizing the balance between throughput, the rate at which a system produces output, and Work-in-Progress (WIP) inventory, which refers to the amount of material currently being processed within the system.

The shape and characteristics of OC (see Figure 1) are influenced by variability. As discussed in "Factory Physics" by Hopp and Spearman 2011, higher variability flattens the OC, which limits the potential increases in throughput achieved by raising WIP at the same speed. Understanding and managing the operating point is essential for effective operations management. By identifying the optimal operating point on the curve, managers can find a balance between the desire for high throughput and the costs associated with maintaining excessive WIP. This balance requires consideration of factors such as inventory holding costs, customer service levels, and the overall efficiency of the system (Vercraene and Gayon 2013). The utility of the OC goes beyond simply understanding the relationship between throughput and WIP; it serves as a powerful tool for various production operations:

- **Capacity Planning:** It helps to determine the optimal capacity level needed to meet demand while minimizing WIP to optimize production speed and associated costs.
- **Production Scheduling:** Developing effective production schedules that balance throughput with WIP levels, ensuring smooth flow, speed, and timely delivery.
- **Inventory Control:** Guides inventory management decisions, helping maintain appropriate WIP levels to support production without incurring excessive holding costs.
- **Process Improvement:** Understanding the impact of variability, managers can pinpoint opportunities for process improvement to improve throughput, increase speed, and reduce WIP.
- **Bottleneck Management:** Pinpoint resource bottlenecks in the system, allowing for targeted interventions (such as avoidance of bottleneck starvation, optimized maintenance schedules, or investments to improve overall performance).

OCs are essential tools for predicting future performance and outcomes. They help managers anticipate how changes in WIP will affect throughput and speed. This information supports informed decision-making about resource allocation and process improvement initiatives. In addition, the curve highlights the importance of managing variability to improve system performance. Most important and as emphasized, e.g. in "Lean Thinking" by Womack and Jones 1997, reducing variability results in a steeper OC, which allows for increased throughput at the same speed and vice versa.

2.3 Components of the Operating Curve

The OC is a pivotal tool in semiconductor manufacturing, as it visualizes the efficiency of a process and the variability that disrupts it. By illustrating how process variability impacts performance and how

Table 1: Key performance metrics and their meaning in manufacturing systems.

Description	Formula
Cycle Time (CT) Time a unit of work spends in the system; composed of queuing time (QT) and raw process time (RPT).	$CT = QT + RPT$
Going Rate (GR) Represents the average output per unit of time (e.g., units per hour); used to measure the operational throughput of a process.	$GR = \frac{WIP}{CT}$
Little's Law Relates average number of items in the system (L), arrival rate (λ), and average time in the system (W).	$L = \lambda \cdot W$
Work-in-Progress (WIP) Number of items simultaneously in process, calculated as the product of cycle time (CT) and going rate (GR).	$WIP = CT \cdot GR$
Rearranged Little's law Alternative formulation to compute cycle time.	$CT = \frac{WIP}{GR}$
Flow Factor (FF) Ratio of actual cycle time to theoretical raw process time; used to indicate process inefficiency.	$FF = \frac{CT}{RPT}$
Utilization (U) Measures resource usage as the ratio of going rate (throughput) to available capacity. CapaPU describes the capacity of the production unit.	$U = \frac{GR}{CapaPU}$

reducing this variability can improve efficiency, the OC provides vluable information on process optimization, as described in "Factory Physics" (2001) by Hopp and Spearman 2011 (see Table 1).

The most important part is variability, which is quantified using the metric α, that captures inconsistencies in the arrival of WIP or process times within the system. High variability flattens the OC, meaning that increasing utilization produces only marginal increases in throughput.

2.4 The 4 Partners of the Operating Curve

In the context of productivity, the elements that influence variability are described as four partners (4M) (Angelis and Brookes 2012). Those 4Ms are essential for influencing variability and thus efficiency. Ideally, they should have low variability and be synchronized.

- **Human:** Representing the skilled workers who operate machinery, handle materials, and implement methods.
- **Machine:** Includes the equipment and technology to run the unit processes.
- **Method:** Procedures, processes, and techniques used to carry out the work.

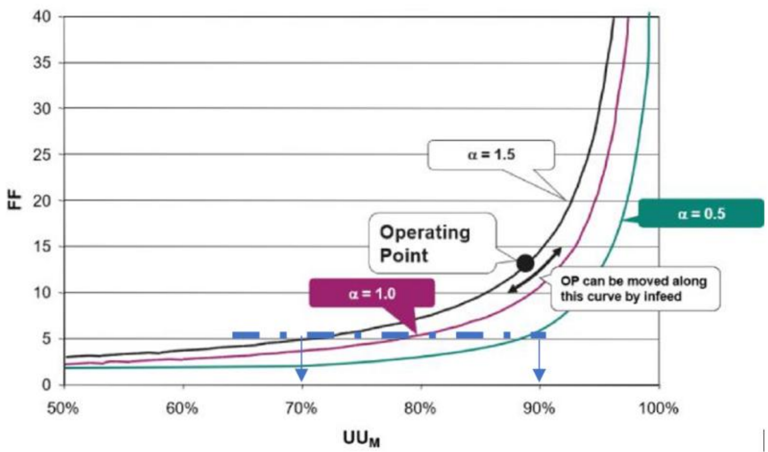

Figure 1: Operating curve: This figure shows the influence of variability. black: α = 1.5, purple: α = 1, green: α = 0.5 (Schmielau and Bisslich 2024). At α = 0.5, utilization rises from 70% to 90%, improving cost position by approximately 10% in capital-cost-dominant fabs compared to an alpha of 1.5.

- **Material:** Materials that are processed or transformed to create the final product: In semiconductor manufacturing, the most important material is the preprocessed silicon wafer for the last step of the process.

2.5 Defining Non-Manufacturing Processes in the Global Semiconductor Supply Chain

When comparing manufacturing processes to non-manufacturing processes in the semiconductor supply chain, our group of experts has developed the following preliminary definition: "non-manufacturing processes are activities within a semiconductor supply chain that do not directly add physical value to chips or wafers." Wafer processing occurs in front-end (FE) fabs, while chip processing takes place in back-end (BE) fabs. In practice, we categorized non-manufacturing processes within global semiconductor supply chains into three distinct areas.

a. **Direct supporting Process Flows:** These include workflows related to existing semiconductor operations, which are directly integrated within the value-added process flows, such as the shipment of products from location A to B.
b. **Indirect supporting Process Flows:** These involve the creation and planning of new workflows required for new semiconductor processes, such as creating master data or supporting processes such as analyzing processes (not part of the main manufacturing flow) or production planning.
c. **Enabler Process Flows:** These are the supporting functions that ensure the smooth operation of both existing and new process flows, such as administrative processes or hiring activities.

	machine	method	material	human
manufacturing	medium-high	medium	low	low
non-manufacturing	low	medium	low	high

Figure 2: 4 partners switching in non-manufacturing: this figure shows the expectable switch in the 4 partners methodology that needs to be further evaluated.

2.6 Operating Curves in the Non-Manufacturing Context

In non-manufacturing processes, we expect the 4M contribution to variability to shift. The human becomes a more dominant part, while the machine (often only the computer remaining) lacks relevance. We expect the human element to be the by far most dominant factor.

When it comes to variability, the approach to efficiency changes significantly in non-manufacturing contexts. In these situations, variability arises not from machine-driven factors, but rather from human actions and the methods employed. Consequently, the strategy applied for machines needs to be transferred to human or a different strategy is required for non-manufacturing workflows.

On the one hand, we expect that variability can be reduced. Unverified and unvalidated processes can contribute to greater flexibility by using higher-skilled personnel and increasing human availability. For instance, adopting ’follow the sun’ approaches can increase human availability and enhance productivity across different time zones in global supply chains.

However, we also recognize that there will be processes or situations involving process changes in which variability cannot be completely eliminated, as is often the case in manufacturing. In these instances, unverified and unvalidated solutions may involve buffering and balancing strategies to manage variability effectively.

3 RESEARCH METHODOLOGY

This conceptual paper lays the foundation for a future research agenda.

The research is structured in multiple progressive stages, starting with a thorough review of the existing literature. It will also include feedback received following the publication of this conceptual paper, all while utilizing the OC principles and Little’s law.

First, we will identify the differences between manufacturing and non-manufacturing environments while verifying and validating the shift within the 4M contribution to variability. In the next stage, we will a) measure raw process time and actual times to determine FF efficiency and comparable FF data from non-manufacturing processes to gain initial insights into the efficiency and effectiveness of these workflows; and b) observe the process change rate to gain initial insights into the time efficiency of these workflows.

To achieve this, non-manufacturing processes will be described using BPMN (Business Process Modeling Notation) software (Object Management Group 2011), creating swim lanes (Sharp and McDermott 2009) and structured data with ontologies (Uschold and Gruninger 2004; Ehm, Ramzy, et al. 2022). Both enable measurements of the FF. It will then serve as a key indicator for evaluating the variability reduction potential, which we expect to directly link to an increase in efficiency.

After analyzing the data, potential intervention needs will be identified. Subsequently, case studies will be conducted in a chosen non-manufacturing context.

By incorporating real-world data, manufacturing principles can be managed in a thorough and reflective manner (Glässer 2012). In the final phase of the investigation, we plan to carry out monitoring and evaluation using the ADKAR (Awareness, Desire, Knowledge, Ability, Reinforcement) model (Majka 2021) and simulations with AnyLogic.

4 APPLICATION ON NON-MANUFACTURING ENABLER PROCESS FLOWS

The following chapter shows the application of the OC methodology with FF analysis to trigger improvement ideas. It is grounded in the aforementioned concept of OC management, with a strong emphasis on synchronization and variability reduction across the 4Ms. To validate these principles, the methodology was applied to two specific hiring cases defined as enabler process flows. The approach involved a systematic collection of data both before and after the synchronization of the four partners. The FF is calculated on the basis of the raw process time and the process time, as stated in 2.3.

The first use case focuses on the process of creating certificates of employment (CE). They are issued by an employer to an employee when the employment relationship ends. These certificates provide information about the type and duration of employment, and often include an evaluation of the employee’s

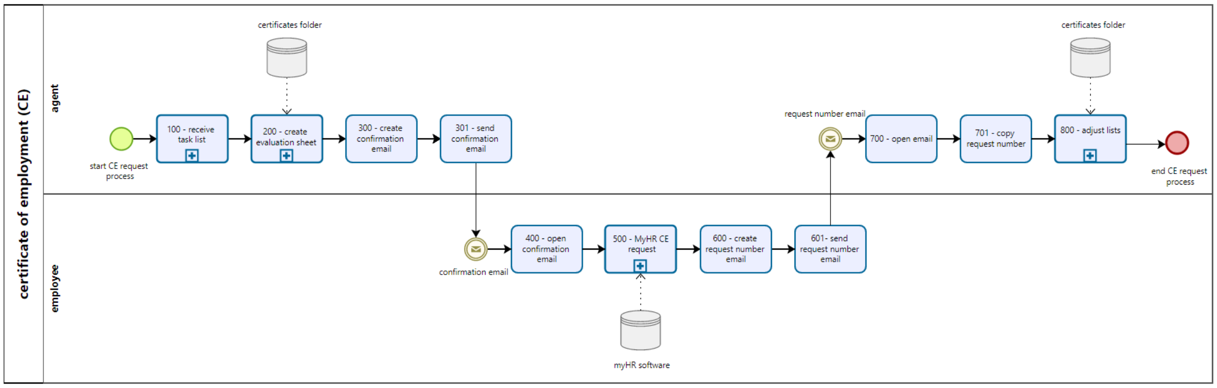

Figure 3: CE unit process BPMN visualization (Lauter 2025a): the figure shows the process flow of the used CE unit processes.

performance and behavior (Grau and Watzka 2016). To clearly represent this process and measure the raw process time, individual steps have been depicted using BPMN.

Figure 4a illustrates the evolution of the FF prior to the synchronization of the 4Ms. For this analysis, seven samples were evaluated. The results show a mean FF of 73.8, with a median of 72 and a standard deviation of 49.

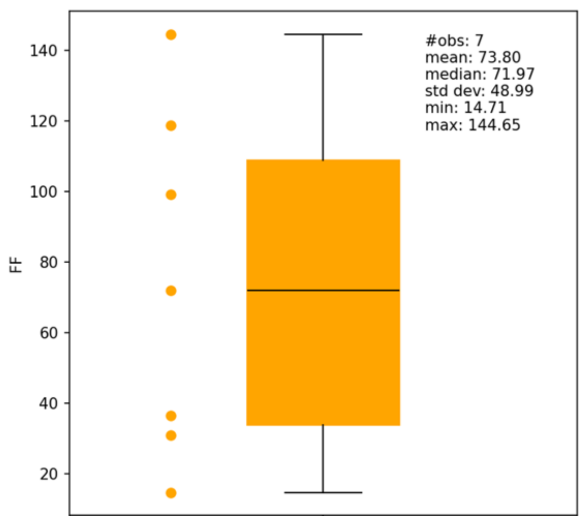

Figure 4a: Before synchronization.

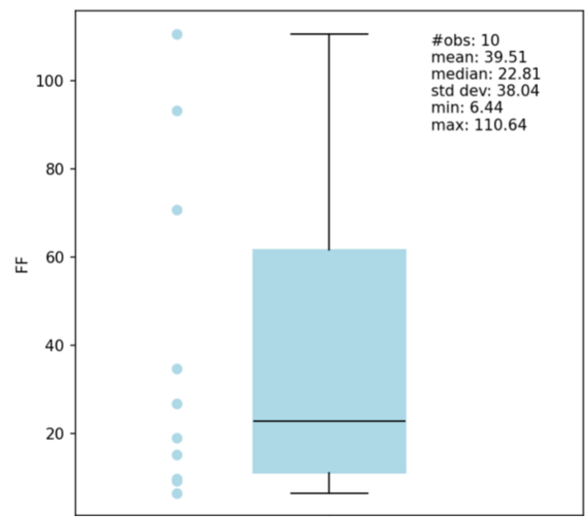

Figure 4b: After synchronization.

Figure 4b presents the FF after the synchronization, based on ten samples. Following the intervention, the mean FF was nearly halved, with a value of 39.5, while the median decreased to 22.8, representing a reduction to roughly one-third of its initial value. The standard deviation decreased by 22%, reaching a value of 38.04.

The second use case focuses on the new hiring (NH) process, which is defined as the initiation of a contract request. This process encompasses the steps required to formalize and approve a contract between an employer and a new employee. It involves the definition of job requirements, the approval of internal stakeholders, and the generation of the employment contract. To clearly represent this process and measure the raw process time, individual steps have been depicted using BPMN.

Figure 6a presents data from six use cases prior to synchronization, revealing a mean FF of 33.1 and a median of 31.5. The standard deviation was recorded at 22.6.

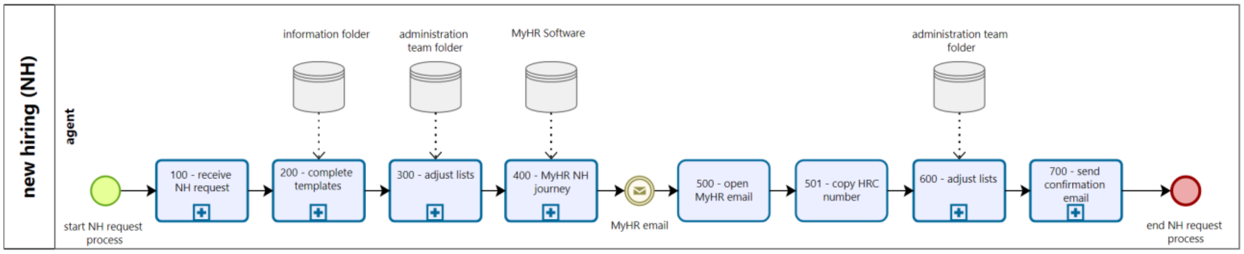

Figure 5: NH unit processes BPMN visualization (Lauter 2025b): the figure shows the process flow of the used NH unit processes.

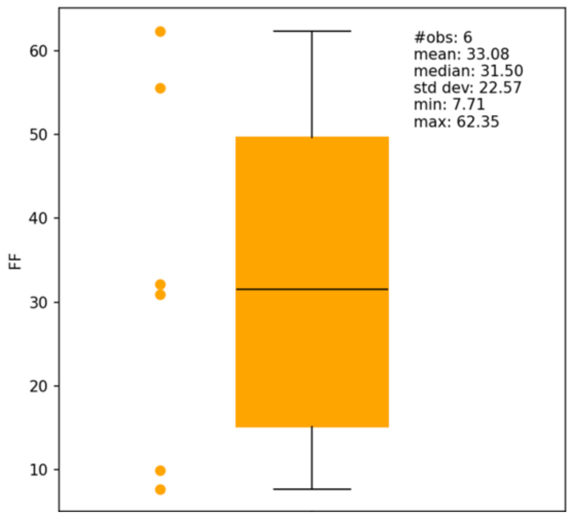

Figure 6a: Before synchronization.

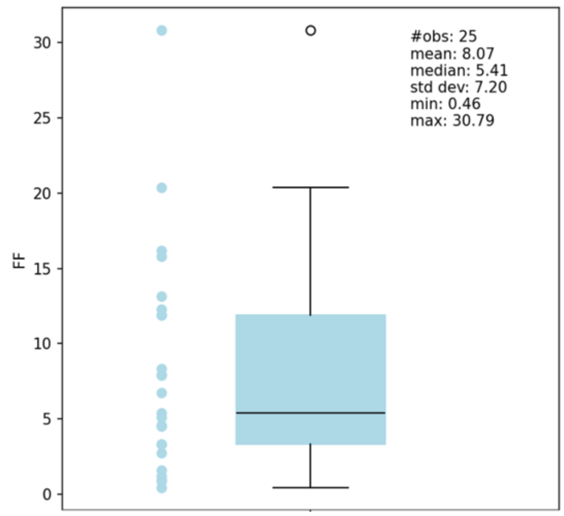

Figure 6b: After synchronization.

As illustrated in 6b, after the synchronization intervention, both the mean and median FF values were reduced significantly, falling to between one-quarter and one-sixth of their original values. The primary significance lies in the reduction of the standard deviation, which decreased for 68% to 7.2. This represents a near threefold reduction.

Across both use cases, the results consistently show significant improvements. In the first use case, the process of creating employment references demonstrated a reduction in both mean and median FF values, with variability (as reflected across in the standard deviation) also noticeably reduced. Similarly, the second use case, focusing on NH process, saw a nearly halving of the mean FF and substantial reductions in the standard deviation. Our preliminary conclusion is that the application (in this first case only the measurement and communication of the FF) of OC management, within non-manufacturing environments, particularly through the synchronization and reduction of variability across four key partners, indicates measurable success.

It should be noted that an absolute FF of 20+ seems to be not a great achievement, when we know the manufacturing FFs of 2-4. However, the measurement showed, from the manufacturing point of view, that an inefficient initial process with a FF>30, the relative improvement of 30% is significant and not all potentials have yet been realized.

5 CONCLUSION AND FUTURE WORK

The application of the manufacturing principles of OC management to non-manufacturing processes within the global semiconductor supply chain, especially focusing on variability analysis through FF measurements, can reveal inefficiencies.

As outlined in this conceptual paper, fab-focused semiconductor manufacturing environments have long benefited from OC management, including Little's law, lean principles, and FF efficiency analysis. This systematic approach provided improved efficiency through reduced variability. Much of today's value creation in the contemporary global semiconductor supply chain is enabled beyond a single fab in non-manufacturing processes.

The shown results indicate the applicability of OC management principles, especially and initial FF analysis, within non-manufacturing environments. By focusing on synchronization and thus overall variability reduction, non-manufacturing processes that might traditionally be seen as too intangible for structured improvement, might achieve significant gains in performance and alignment. As such, these findings may pave the way for broader adoption of these principles across non-manufacturing domains, further driving operational excellence in the global semiconductor industry.

The promising first results of the two use cases indicate that applying semiconductor manufacturing principles (i.e., in our case, OC management) to non-manufacturing processes could be highly beneficial. We aim to bring proven optimization methodologies, such as the OC, FF, 4M, variability reduction, and synchronization, to the expected more human-driven non-manufacturing process flows. Our next experiments will be for the provision of master data and of engineering samples.

We invite you to join us on our proposed pathway to improve the efficiency and the effectiveness of global semiconductor supply chains with this conceptual paper. We hope that it will lay the foundation for future theoretical and empirical research aimed at aligning non-manufacturing processes more closely with manufacturing ones and driving greater efficiency in our rapidly evolving world.

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