I. EXECUTIVE SUMMARY

Since the 1970s, manufacturers have sought to attain the benefits of the Toyota model of lean manufacturing. Yet the techniques employed by Toyota have proven elusive or even unattainable to many manufacturers because Lean is not well suited to high-mix environments. These environments have thousands of products, dozens of work centers, and display significantly more process and demand variability than the traditional high-volume environment seen at Toyota.

This paper describes how to improve manufacturing performance in a high mix environment using lean manufacturing techniques. It concentrates on how high mix environments are different from high volume environments, and therefore require extensions to traditional lean manufacturing techniques via flow path management.

Starting with a background on why improving manufacturing performance is important, the paper describes how lean manufacturing has helped high volume manufacturers improve productivity and profit margin. Unfortunately, applying the same techniques in high mix environments poses challenges, so this paper presents seven areas where modifications to traditional Lean techniques can create innovative approaches that allow high mix environments to achieve similar benefits.

Written for manufacturing executives and plant managers looking to improve manufacturing performance in a high mix environment, the paper assumes some basic knowledge of lean manufacturing techniques as applied in high volume environments, e.g., Kanban cards, level-loading, etc.

II. BACKGROUND: WHY IMPROVE MANUFACTURING PERFORMANCE?

Manufacturing executives face increasing competitive pressure to improve manufacturing performance and supply chain management. Outsourcing, off-shore competition, eroding profit margins, and increasingly demanding customers are challenging traditional levels of performance and forcing manufacturing plants to either improve or perish. To deliver the products demanded by customers and the returns demanded by investors, companies must increasingly look to manufacturing to find performance improvements that maintain profit margins and provide competitive advantages. Moreover, manufacturers need to find ways to improve overall supply chain management across their suppliers, manufacturing sites, and complex distribution networks.

Market forces continue to put more and more power into the hands of customers, and manufacturing companies are finding it necessary to offer an ever-increasing selection of custom products. This customization trend requires that high-volume, repetitive mass production environments take on some of the traits of high-mix production environments. Product lifecycles have gotten shorter, leading to additional product proliferation and mix challenges. More and more industries are moving from a make-to-stock to a make-to-order environment. Companies such as Dell, that led their industries in this trend, have built enormous competitive advantage.

Bottom line, producing a quality product at low cost no longer guarantees success in today’s market. The ability to build exactly what the customer wants and deliver it quickly is the new definition of competitive strength, requiring manufacturers to reach best in class levels in the following four areas:
1) **Throughput** - defined as the amount shipped from the plant. A focus on throughput allows manufacturers to measure something more meaningful—actual saleable products shipped—versus machine efficiencies or utilization.

2) **Cycle time** - defined as the time to convert raw materials into delivered product. Cycle time improvements are a basic tenet of Lean because they directly attack waste—waste in inventory, queue time, and other non-value added aspects of manufacturing.

3) **Customer service** - measured with metrics such as On-Time-Delivery or Fill Rates. Metrics focused on customer service ensure that the most important characteristic of your operation—satisfying the customer—is achieved.

4) **Inventory Levels** - including raw materials, work-in-progress (WIP) and finished goods. Inventory is a necessary evil because without raw materials or work-in-process inventory, manufacturers can’t make products. Still, idle and/or excess inventory is one of the most serious resource drains in a manufacturing operation, so inventory optimization is a key element of Lean as well.

Lean manufacturing concepts help companies improve cycle times and inventory positions, which in turn positively impacts throughput which increases customer satisfaction. Unfortunately, applying these concepts has proved to be difficult in many forms of manufacturing. To clarify, most manufacturing operations can be classified as one of five generic flow types¹, as shown in Figure 1.

**Figure 1:** The Manufacturing Continuum

![Image of the Manufacturing Continuum](image.png)

Lean concepts have been more successfully applied to the rightmost types of manufacturing. Where can manufacturing managers in the three leftmost environments look for techniques to improve manufacturing performance? The balance of this whitepaper focuses on these high mix environments and how lean manufacturing principles can be adapted to address their needs as well.

**III. LEAN MANUFACTURING: THE PREFERRED IMPROVEMENT METHODOLOGY FOR HIGH VOLUME, REPETITIVE ENVIRONMENTS**

Readers familiar with lean manufacturing will know that its origins lie in high volume manufacturing at Toyota. The Toyota Production System (TPS) methodology has a proven track record for improving performance and eliminating waste. The approach was originally developed in the 1950's², and has been continuously improved in subsequent years³, leading many to regard Toyota as the recognized leader in automotive manufacturing.⁴ Toyota Motors pioneered the development of several manufacturing management philosophies and techniques that collectively could be applied without the use of any software tools.

As currently adopted, Lean incorporates supporting techniques from a variety of other promising fields including The Theory of Constraints, Just in Time Inventory Management, and Six Sigma.
The groundbreaking work of Womack and Jones, for example, lists five principles of Lean Thinking:

- Specify Value
- Identify the Value Stream
- Make value flow
- Let customers pull
- Pursue perfection

These approaches have proven so successful that numerous other manufacturers have started deploying various versions of these systems, spawning the Lean movement. According to the 2003 Industry Week/Manufacturing Performance Institute Census of Manufacturers, a little over one-third of U.S. manufacturers (36%) identify lean manufacturing as their primary improvement methodology. The movement has been bolstered by reports from firms like AMR Research that promote the value of “Demand-Driven Supply Networks” for improving supply chain performance.

Customer demands and product proliferation are pushing companies away from high volume towards high mix (as shown in Figure 2). Competitive pressures are pushing companies towards the productivity improvements and waste reduction inherent in Lean Manufacturing. Increasingly, manufacturing companies must evolve to be both high mix and Lean.

![Figure 2: Staying Ahead of Market Demands](image)

### IV. HIGH MIX ENVIRONMENTS: LEAN’S BREAKING POINT

The bulk of successful Lean implementations are in high volume, repetitive environments which is not surprising given its roots in automotive manufacturing. TPS techniques work well in high volume, low mix environments because of their inherent simplicity, but they have proven difficult to implement in less stable, more highly complex factories. Recently though, lean manufacturing has begun to expand beyond traditional high volume automotive environments into industries as diverse as pharmaceuticals, aircraft manufacturing, electronics, industrial products, and even office/administrative applications as practitioners are learning how to adapt the techniques.

High-mix environments differ from high volume environments in many ways as the table below depicts and managing the flow of materials through a high mix environment is different as well, requiring extensions to traditional Lean techniques and terminology.
For instance, in traditional high volume Lean environments, equipment is dedicated to a single product family whenever possible. But in high mix environments, where a plant is producing hundreds or thousands of products, equipment must nearly always be shared across product lines. Buying dedicated equipment, even smaller capacity equipment, would needlessly waste millions of dollars of capital.

Implementation of techniques like pull scheduling provides another example. In traditional high volume Lean, pull scheduling is implemented using Kanban cards, where each card has a part number associated with it. Every pulled card signals the need to produce more of that part number. But in high mix environments, this traditional Kanban implementation would require a company to print thousands of cards, one for each part number. The plant would need to produce and hold inventory for at least one item of every part number, even if there is no customer demand for that particular item, tying up millions of dollars in unnecessary inventory.

Challenges aside, due to the trend toward customization and the proven benefits of lean manufacturing, it is worth the effort to modify standard techniques so that Lean principles can be utilized in a high mix environment.

V. LEAN FOR HIGH MIX MANUFACTURING

Industry practitioners have identified seven areas where lean techniques can be extended to address the characteristics of high mix manufacturing:

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<th>High Mix</th>
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Table 2: Extending Lean to High Mix plants
The following describes in detail how each of these Lean techniques can be successfully implemented in a high mix plant.

1. **Flow Paths**: Value Streams for Product Families.

Traditional high volume lean projects start by grouping products into a small set of product families, then creating value streams for each family. The approach involves designing cells that have equipment dedicated to the production of a single product family, and then implementing single-piece flow through that cell.

This approach is very effective in high volume environments like automotive where there are a relatively small number of products and dedicating equipment doesn't pose a resource problem. High mix environments, however; have thousands of products visiting dozens of work centers using a variety of possible routings. As such, a more general approach to defining value streams is required to (a) accommodate a larger number of possible product families, and (b) enable equipment sharing among multiple product families.

High mix environments require a more general classification of product groupings that support the goal of establishing flow, but also allow equipment to be shared across product families.

We call this classification a “Flow Path”. Flow Paths are a fundamental concept that allows high mix environments to implement Lean. By grouping products into families that visit similar pieces of equipment, flow paths provide a means to manage thousands of products through complex routings without requiring dedicated equipment.

Flow Paths are more than just simplified product groupings (as described in Duggan10). Flow paths—groups of products that visit similar work centers—facilitate the logical division of the plant into multiple flows, each of which can be considered a “focused factory”, independent of the others. Multiple flow paths can be defined for a plant, but a product can belong to only one flow path.

Flow Path Management (FPM) is defined as "the management techniques used to control the movement of materials through a plant’s flow paths." FPM concentrates on optimizing the flow of materials through each path to maximize throughput and customer service while minimizing inventory and cycle time. Flow Path Management builds on decades of research showing the benefits of focused factories11, but extends this research to incorporate the lessons learned as lean manufacturing techniques have been applied in high mix environments.

FPM shares several key principles with traditional high volume lean manufacturing and the Toyota Production System (TPS), including the elimination of waste and the application of pull scheduling. But while TPS was invented for high volume automotive production, FPM was invented for high mix industries such as pharmaceuticals, metals, and electronics. One of
The reasons for FPM’s success in these industries is that by breaking the process down into flow paths, some of the complexity of the problem is removed—allowing visibility into the plant’s dynamics on a more manageable scale.

2. **Organization Structures.**

Traditional high volume lean environments tend to organize production workers like they organize production equipment, dedicating people to a cell. They then balance work content among people in the cell to ensure capacity is matched to the takt time of the market.

But just as high mix environments can’t dedicate equipment to a small set of product families, they can’t dedicate people, either. People must be more flexible, and able to work on a variety of products as demand shifts.12

As opposed to the traditional structure of ‘departments’ and functional layouts, a high mix plant seeking to embrace Lean needs to organize around the flow paths described above.

Flow Path leaders (similar to cell leaders in a low mix facility) can track the flow of materials through their flow path and (using the proper tools) identify and alleviate any impediments to effective product flow. With the organization aligned according to these flow paths, metrics can be created and incentives administered enabling management to all levels of the organization on a reasonable and actionable scale.

3. **Performance Measures.**

Traditional Lean relies wherever possible on visual, line of sight boards on the shop floor to track performance. Heijunka boards, for example, are used to communicate what jobs should be produced throughout the shift, and provide an easy way to measure performance, but in high mix environments, it is usually impossible to use manual or card-based systems to communicate the schedule or to track performance. For example, Heijunka boards would require thousands of boxes and numerous people to shuffle and distribute production cards in a high mix environment.

Contrary to traditional Lean implementations, it has proven difficult to establish visual signals in high mix environments; thus, performance measures in a high mix environment need to track and communicate results of each flow path. Each flow path needs metrics that tell workers, collectively, how the entire flow path is performing.

Traditional metrics, like equipment utilization or department budgets, are tuned to vertical silos rather than horizontal product flows. So companies implementing Lean generally need to deemphasize or eliminate traditional metrics and concentrate instead on the following three measures that track the movement of material to the customer through each flow path:

a. **Cycle time**: This is a measure of the time it takes for the product to flow through the factory floor.

b. **Throughput**: Throughput is a measure of the production rate (of saleable product) of the factory.

c. **Delivery Performance**: This is a measure of the ability of the factory to meet its delivery commitments to customers. It is a key indicator of customer satisfaction and has a direct impact on revenue generation potential.

There are two primary differences between these metrics and traditional ones. First, compared to traditional non-Lean environments, these metrics emphasize product flow and customer value instead of efficiency and department-based metrics. Second, compared to traditional high volume Lean environments, these metrics utilize software to collect data and
communicate performance measures instead of relying solely on shop floor boards and visual signals.

4. **Pull Scheduling.**

‘Pull Scheduling’ is a demand-driven method of material release. New material is produced **only after** existing material has been consumed. Pull scheduling contrasts with older methods that allowed computer programs to ‘push’ material onto the floor- regardless of whether there was room or a need.

Traditional high volume Lean implements pull scheduling using Kanban cards. Each card includes a part number and quantity. When a product is sold or consumed, the card is moved to the prior operation, where an operator produces the specified quantity of that part and then moves the inventory with the card attached to the next operation.

For obvious reasons, this gets quite complicated in a high mix environment. Inventory for each part in process is on the floor at all times, even if there is no immediate demand for that part and there are thousands of parts. Variability in demand dictates that appropriate levels of inventory for each part will vary over time, requiring management to add or remove cards quite often. Finally, work centers will frequently see different mixes of products. Bottlenecks will likely shift from one work center to another leaving the number of cards assigned between pairs of machines out of balance, risking starvation of the new bottleneck.

Given the issues with traditional Kanban, practitioners have developed several alternative forms of pull scheduling better suited for high mix environments. While the techniques are known by a variety of names such as “Generic Kanban”, CONWIP, Drum Buffer Rope, or POLCA, they all share common techniques to (a) have the “card” represent a flow path or generic family of parts, (b) have the “card” able to float more freely to buffer the bottleneck from starvation, and (c) reduce inventory while still protecting throughput from sources of variability like product demand or unplanned equipment downtime.\(^\text{13}\)

One of the key benefits of Flow Path Management is the ability to apply whichever variety of pull scheduling is most appropriate for the conditions in the business. A high-mix plant may have several flow paths, and each flow path can utilize the method of pull most appropriate for its business. For example, high volume, repetitive flow paths might best utilize traditional Kanban, while high mix flow paths might best utilize the more generic CONWIP approach to pull scheduling. Many of these types of pull methods utilize computer systems to execute day-to-day decisions on the shop floor. Kanban approaches are usually simple enough to be done manually by physically transferring cards between inventory units. As plant complexity increases, it is common for software to be utilized to track pull ‘signals’ within the plant.

(“Different Flavors of Pull Scheduling”, another white paper that gives a more in-depth analysis of pull scheduling for high mix environments, is also published by Invistics Corporation and is available from the web site at www.invisitics.com.)

5. **Bottlenecks and Capacity Planning.**

It is no secret that excess capacity (extra machines or staffing) can hide waste and mask many evils within a plant. These large safety nets can be extremely costly in terms of tying up cash, increasing cycle time, or requiring an unacceptable outlay of capital.

Traditional high volume Lean uses rules of thumb and simple calculations to determine the best levels of capacity utilization. For example, many high volume plants aim for a given utilization percentage, say 85%. Such calculations are often driven by accounting standards
and the need to absorb overhead by applying indirect costs to products based on machine hours.

But in high mix environments, setting optimal capacity levels cannot be accomplished using simple rules of thumb. With hundreds of products, each with varying demand and routings, bottleneck resources shift. These bottlenecks constrain total throughput, and management must identify them as the first step in optimizing performance, a technique popularized by *The Goal* and the Theory of Constraints.

Calculating capacity utilization must also be sensitive to variability in equipment processing times, downtimes, setup times, and product demand. Variability, after all, is one of the primary reasons inventory and capacity buffers are needed. By incorporating variability in its calculations, plants can set capacity levels high enough to provide a buffer. Moreover, they can calculate which sources of variability should be attacked first to reduce the need for extra capacity buffers.

6. **Inventory Optimization.**

Inventory is another buffer that can hide waste and mask variability within a plant. As with capacity utilization, traditional high volume Lean uses rules of thumb and simple calculations to determine the best levels of inventory. For example, inventory levels are set in most Kanban implementations by using calculations based on Little’s Law—inventory equals throughput times cycle time. Kanban card counts are initially calculated by multiplying a cell’s takt time by its expected cycle time. Over time, management slowly reduces the card count to lower the inventory level and expose and fix production problems hidden by that inventory.

In high mix environments, setting optimal inventory levels cannot be accomplished using simple rules of thumb. As variability in demand, product mix, setup times, process times, and machine reliability increase, the duration that a set inventory level is valid becomes increasingly smaller, making a dynamically calculated value necessary. Advanced approaches provide updateable optimal levels, and the same concept holds true for determining optimal inventory policies for raw material or finished goods inventory buffers.

The following graph illustrates the point with a simple example. Cycle time for a product increases as capacity utilization increases. The line marked “high variability” shows a plant that has high variability in product demand, processing times, setup times, and equipment downtime. The line marked “low variability” shows a plant with identical average product demand, processing times, setup times, and equipment availability, but with lower variability in these values. By using operations research to draw these two lines, one can see how the cycle time for the low variability plant is much shorter. Management can use a graph like this to decide how much capacity utilization, cycle time, and inventory are optimal for their current levels of variability. Moreover, they could investigate “what-if” scenarios to see how much better their plant can perform with
lower levels of variability, and use this analysis to target improvement efforts like setup time reductions that will reduce the need for inventory and/or capacity buffers.

FPM is more likely to utilize advanced inventory optimization methods than approaches such as TPS because high mix environments generally have more variability in demand and supply. This additional variability requires more advanced inventory optimization. For example, FPM embraces advanced operations research techniques for optimizing WIP levels, lot sizes, cycle times, and customer service levels.

7. **Lot Sizing**

Lean thinking promotes single piece flow. But when setup times prevent lot sizes of one, parts must be produced in lots that share a common setup. (The term lot size is often called batch size or campaign sizes. The terms generally mean how much a product should be produced each time it is produced.)

Traditional high volume lean uses rules of thumb called “Every Part Every Interval” (EPEI) to set lot sizes. In this calculation, management sets a target capacity utilization, such as 85%, and then finds the smallest interval of time such that utilization of equipment will be equal to the target of 85% assuming every part is produced during that interval. The lot size for each part is then calculated by forecasting demand for that part over that interval.

Again, because of variability, this approach is unworkable in high mix environment. It suffers from two weaknesses. First, the appropriate target capacity utilization needs to be optimized based on variability. A plant with high variability might optimize utilization at 70%, while one with low variability would perform better at 90%. Second, the correct lot size for each part will vary as product demand varies and as production capacity varies. For example, if demand for one flow path increases, the optimal lot size for products on that flow path will increase. Only by optimizing the lot sizes to reflect this variability will high mix environments counter these weaknesses.

New operations research methods have provided techniques to optimize these lots sizes, taking multiple sources of variability into account in their calculations.

**VI. CONCLUSION**

For over 30 years, high-volume, repetitive manufacturing environments have benefited from lean manufacturing methodologies. Unfortunately, those techniques did not translate well to a high mix environment with huge numbers of products and high variability in products and processes.

Lean manufacturing techniques can be adapted to high mix environments when the effort is focused on:

- Changing traditional metrics and measurements of performance
- Using flow path management to derive more flexible approaches to defining value streams and organizational structure
- Utilizing alternate means of calculating inventory, capacity planning and lot sizing.

While many lean manufacturing techniques can be manually implemented in high volume, repetitive environments, processes in high mix environments can become much more complex. Manufacturers can benefit from using available software solutions for implementing flow path management in a high mix environment to take advantage of lean manufacturing techniques.
VII. LEARN MORE ABOUT LEAN IN A HIGH MIX ENVIRONMENT

To learn more about how Invistics software applies cutting edge operations research techniques to make implementing lean in a high mix environment possible, please visit www.Invistics.com or call 800-601-3456.

VIII. ABOUT INVISTICS

Invistics helps companies break through performance barriers. We go beyond analyzing factory information, to actually help you determine the best course of action at any point in time in the manufacturing process. From the manufacturing executive to the shop floor operator, Invistics customers transform factories into world-class operations focused on continuous improvement and profitability.

Invistics Flow Path Management System® is a Manufacturing Performance Management solution that was designed by experienced manufacturing veterans and leading operations scholars. For years, we were in your shoes. We learned in practice that the only way to create lasting, sustainable improvement is to understand your limitations, and eliminate them. With Invistics, you are no longer dependent on an army of consultants, or a victim to the annual ‘next big thing’ project.

For more information about Invistics MPM Software Suite – Flow Path Management System, please visit www.invistics.com or call 800-601-3456.

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