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Future-ready industries: Smart, sustainable, and circular resource management through Industrial Symbiosis (IS)

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Module 4.2 Lean Industrial Symbiosis

Module General Aim

The purpose of this unit is to provide a comprehensive understanding of **Lean Industrial Symbiosis (LIS)** as a distinct management methodology.

It aims to demonstrate how Lean Production principles (such as Flow, Pull, and Zero Defects) and Quality management concepts can be applied to Industrial Symbiosis to transform undefined, chaotic waste exchanges into disciplined, standardized, and efficient value streams.

Module Specific Objectives

Upon completion of this unit, learners should be able to:

- *define* and distinguish key Lean principles including “Value, Waste (Muda), Unevenness (Mura), Overburden (Muri), Value Stream, Flow, and the difference between Push and Pull systems.”
- *comprehend* Lean Industrial Symbiosis (LIS) approach, specifically the paradigm shift of viewing waste not as a liability to be discarded, but as a "Secondary Product" that must meet specific customer specifications (Quality, Timing, Volume).
- *identify* the Three Pillars of LIS: Extended Value Stream Mapping (Sus-VSM); Quality at the Source (Zero Defect Symbiosis), and Just-in-Time (JIT) Exchange.
- *analyze* operational challenges in IS, including the matching problem, quality variability, inventory logistics, and information asymmetry and *apply* lean solutions to these challenges

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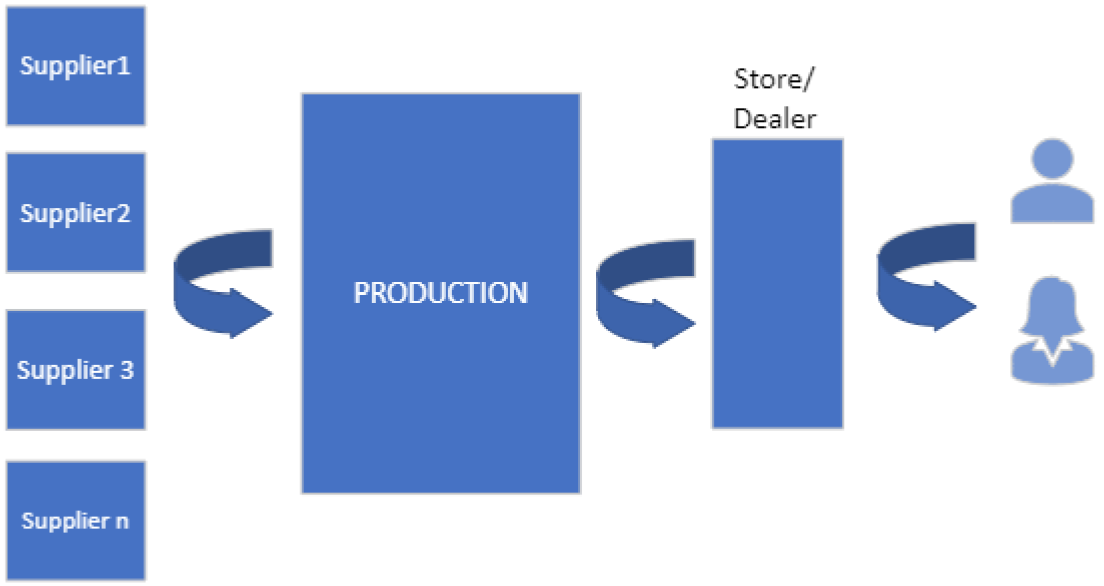
Lean Production

Lean production is an integrated set of activities designed to achieve production using minimal inventories including raw materials, work-in-process, and finished goods.

Parts in needed amount arrive at the next workstation "just-in-time" only when needed and move through the production process in a **PULL** way.

The logic is "nothing will be produced until it is needed and more than is needed".



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Lean Operations

Lean operations work to produce only what customers want and when they want, without waste.

Lean is the **"Pull"** methodology in which the production process is initiated only when the customer requests it.

Waste, variability, and throughput are the fundamental issues focused on in lean firms/processes.

PRINCIPLES

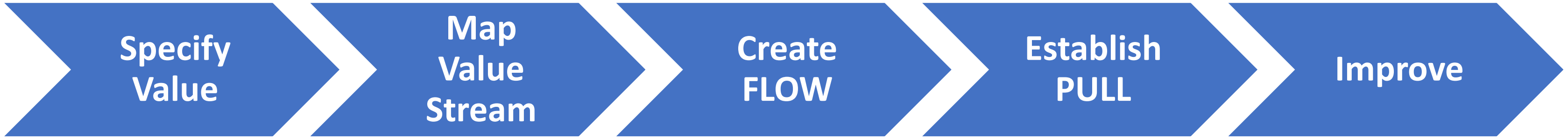
Precisely specify **VALUE:** What customers need and want with products

Map the **VALUE STREAM** and uncover the WASTE and wasteful steps.

Re-design the system so that value **FLOWs** seamlessly.

Establish a **PULL** System where production starts only with customer demand (next/downstream process is your customer)

Continuously improve the system towards **PERFECTION**



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Specify Value → Map Value Stream → Create FLOW → Establish PULL → Improve

- **VALUE** is a set of critical product/service attributes defined by the customer and created by the producer.
- Identification of the VALUE requires close and continues communication between suppliers and customers.
- Anything that does not add value to products from the customer point of view is **WASTE** (“muda” in Japanese)

Seven Wastes (MUDAs)

Overproduction: producing more or earlier than needed

Waiting / Queues: waiting for resources, or recourses waiting to be processed

Transportation: unnecessary movement of resources

Overprocessing: more work than required

Inventory: excess materials or products that are not processed nor needed

Motion / movement: unnecessary movement of people due to insufficient work design

Defects / Defective products: Errors, failures, scraps, rework due to ineffective working condition or resources.

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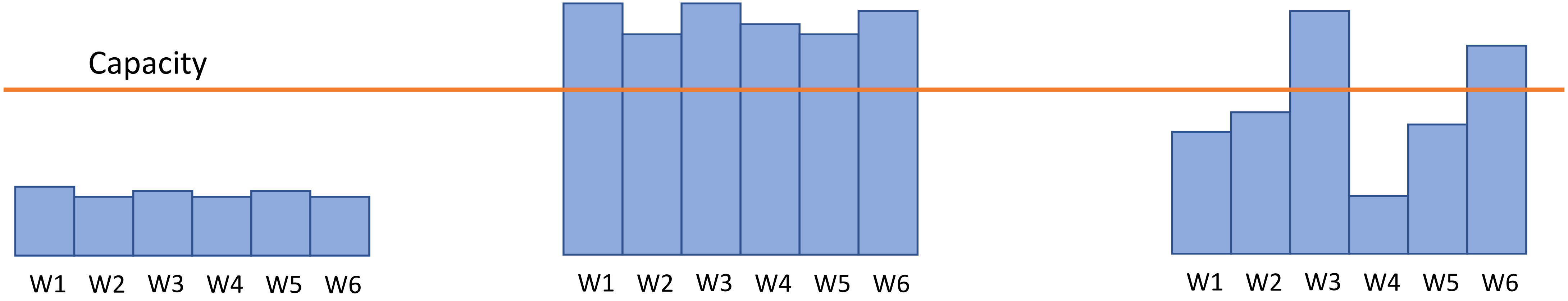
MUDA - MURA - MURI

MUDA:
Waste

MURI:
Overburden (load more than capacity)

MURA:
Unevenness among operations (imbalanced operations)



Anything that does not add value to products from the customer point of view is **WASTE**

giving unnecessary stress to the employees and processes by assigning unrealistic (over) workload on them.
Recovery: Design work processes/facilities to distribute workload evenly over time and across resources

occurs when orders come unevenly from the customer.
or may be result of lack of skills or proper training needed to perform work.
producing in large lots also lead to MURA, as it creates a pile of work or inventory in the system

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Specify Value → Map Value Stream → Create FLOW → Establish PULL → Improve

Seven Green Wastes

Energy: Paying for more power than is required from non-renewable sources rather than using self-produced, clean renewable energy.

Water: The double cost of paying for excess consumption and then paying again to discharge and clean that water.

Materials: Relying on linear "cradle-to-grave" designs instead of cyclical "cradle-to-cradle" reuse.

Source: Wills, B. (2009). *Green intentions: Creating a green value stream to compete and win*. Productivity Press

Garbage: Financial loss from paying for items that are eventually thrown away, combined with the costs of their disposal

Transportation: Paying for unnecessary travel or shipping that burns fossil fuels; solvable through local sourcing, consolidation, and green vehicles.

Emissions: The cost of creating and discharging pollutants, including associated fines and levies.

Biodiversity: The cost of destroying natural landscapes for infrastructure and overharvesting resources faster than they can regenerate.

The value stream is the sequence of processes and actions from raw materials to the finished product or service to create value for the customer.

It includes all the steps and all the information and materials required to transform inputs into outputs (products).

A **VALUE STREAM MAP** visualizes the process flow. It includes information on the key metrics such as cycle times and inventory levels and helps to identify areas of common waste.

Once these areas are identified, the focus is put on eliminating the waste and improving the efficiency of the value stream.

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Specify Value → Map Value Stream → Create FLOW → Establish PULL → Improve

Making the remaining steps (value-creating) of the process flow seamlessly with no interruptions towards customers.

FLOW focuses on establishing a continuous and efficient flow of materials, information, and work processes throughout the production system, from the very beginning to the final stages of the value stream.

FLOW aims to eliminate any waste (unnecessary steps, delays, or interruptions) in the process, and to create a smooth and streamlined workflow.

It requires redefining the connection between the work and functions/departments and shifting from silo thinking to cross-functional process management approach across the company.

Single piece flow instead of batch processing should be aimed wherever possible and reasonable.

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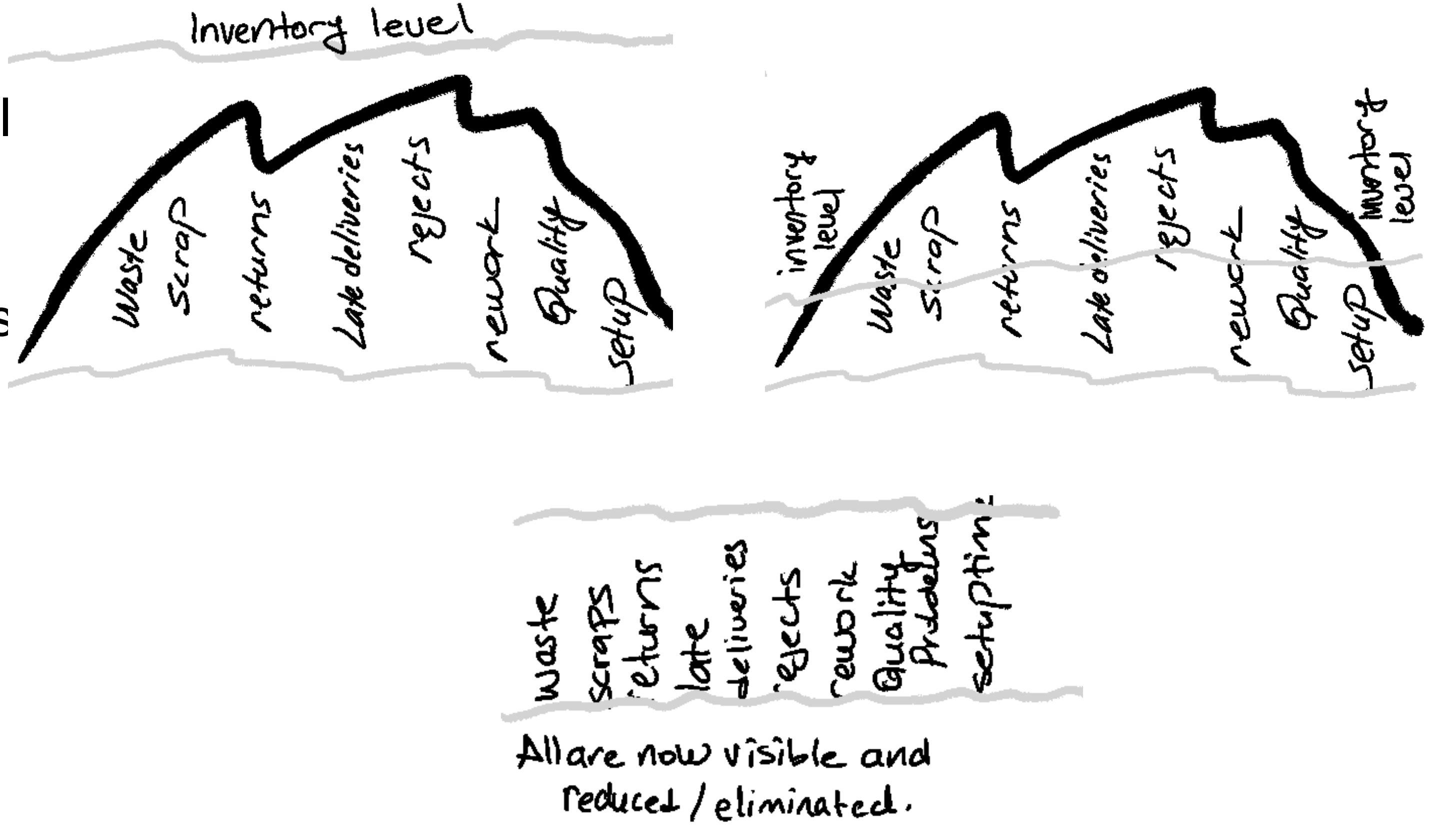
Remove Variability

Variability is any deviation from the optimum process. High variability results in high waste.

variability may be caused by both internal and external factors, such as:

- Poor processes resulting in improper quantities, late, or non-conforming units
- Inadequate maintenance
- Unknown and changing customer demands
- Incomplete or inaccurate drawings, specifications, or bills of material

Reduce inventory, uncover rocks and expose problems



Inventory also hides variability

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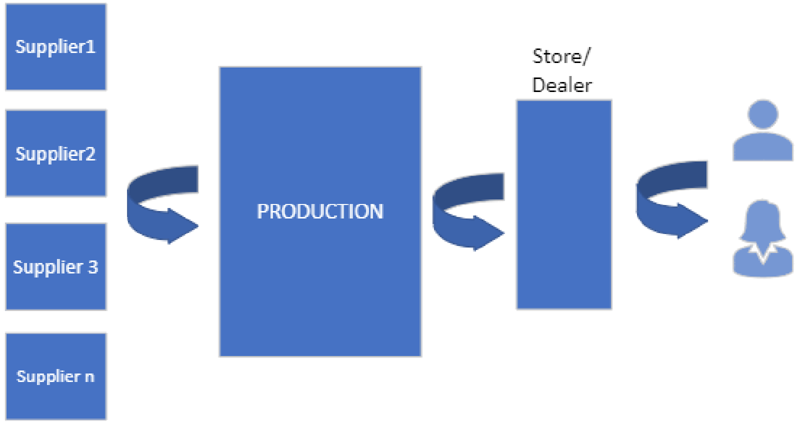
- PULL system ensures that an upstream operation will not produce/process any item until the customer (downstream operation) requests it.
- PULL system is a demand-driven system where production starts with a demand from a real customer and run backwards through all the operations needed to produce the demanded product. (opposite to PUSH systems that produce based on assumptions about just what can be demanded).
- The pull system allows products to be produced in smaller batches and therefore helps improve quality and productivity (shorter lead times).
- Setup reduction (quick change over between small-lots) is essential to achieve PULL system.



Pull system: material is pulled to a workstation just as it is needed

Push system: material is pushed into downstream workstations regardless of whether resources are available.

Improve Throughput

Throughput is the rate at which units move through a process, produced and delivered to the customer.

an important efficiency measure (pieces per hour or units per day).

products stays long in the production process increase cost.

A **pull system** improves throughput. Especially, *pulling* material in small lots, helps to remove inventory cushions and expose inefficiencies in the production process (bottlenecks become visible thanks to reduced inventory levels).

Improved throughput ➔ Reduced cycle time

Push systems dump orders on the downstream stations regardless of the need.

JIT system, where materials arrive *where* they are needed only *when* they are needed, is a powerful strategy for improving operations and throughput

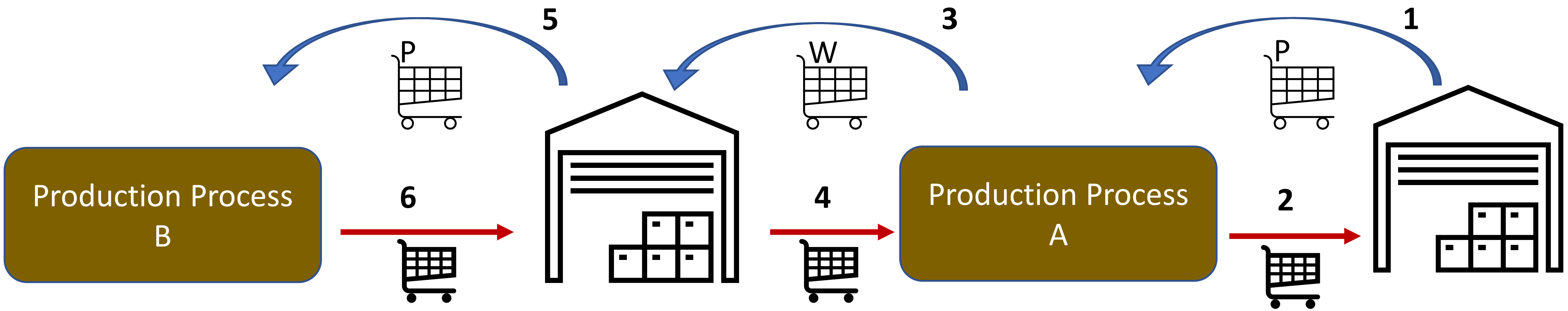
JIT requires a close buyer-supplier relationship

Kanban system

Kanban system, an important enabler of PULL systems, aiming to manage and control the flow of materials and information in lean systems.

Kanban cards (physical or digital) help to create a demand-driven system. They trigger replenishment or production of a product, part, or inventory by conveying the need/demand between the production processes.

Production (P) / Withdrawal (W) Kanban: Specify the needed item (and its quantity) that should be **produced** (P) by **or withdrawal (W)** from a preceding supplier processes.



Specify Value | Map Value Stream | Create FLOW | Establish PULL | Improve

Perfection is the continuous pursuit of excellence and the elimination of waste in all aspects of the production process. The goal is to strive for improved levels of efficiency, quality, and customer satisfaction.

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Lean Industrial Symbiosis (LIS)

Lean Industrial Symbiosis (LIS) is not merely the addition of two concepts; it is a distinct management methodology.

LIS is defined as the application of Lean manufacturing principles (flow, pull, zero defects) to the management of waste exchanges between companies. It transforms the "chaotic" exchange of waste into a disciplined, standardized "Value Stream."

(Nadeem et al., 2025, Cannas et al., 2025, and Simboli et al., 2014)

The Core Philosophy: "Waste as a Product"

In traditional systems, waste is often treated as a liability to be discarded.

In **LIS**, the Generator views the waste stream as a **"Secondary Product"** that must meet customer specifications (Quality, Timing, Volume).
The Receiver views the waste as a **"Standardized Input"** rather than a risky substitute.

The Goal: To eliminate the *Muda* (waste) of disposal by converting it into value, while simultaneously eliminating the *Mura* (variability) that usually creates risk in waste exchanges.

The Three Pillars of LIS

Extended Value Stream Mapping (Sus-VSM): Using tools like **Sustainable VSM** (Faulkner & Badurdeen, 2014), managers map the flow of materials *between* companies. This visualizes the "Hidden Factory" of waste generation. It identifies exactly *where* material loss occurs and *when* it is available, allowing for the synchronization of the Generator’s "Push" with the Receiver’s "Pull."

Quality at the Source (Zero Defect Symbiosis): Application of **Six Sigma (DMAIC)** and **Statistical Process Control (SPC)** to the waste stream ensures that the chemical and physical properties of the by-product are stable. If the waste doesn't meet the "spec," the line stops— just as it would for a primary product defect.

Just-in-Time (JIT) Exchange: Using **Heijunka (Leveling)** and **Kanban** signals between firms, instead of accumulating massive piles of waste (which requires warehousing), the system is optimized so that waste is transported in smaller, more frequent batches that match the consumption rate of the receiver (Network Optimization).

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Operational challenges of Industrial Symbiosis

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Operational challenges of Industrial Symbiosis

The "Matching" Problem (Supply vs. Demand Mismatches)

Quality Variability and Uncertainty

Inventory and Storage Logistics

Information Asymmetry and Trust

Interference with Core Processes

The most fundamental operational barrier is the misalignment between the waste generator's output and the user's input requirements. This manifests in three specific dimensions(Herczeg et al., 2017):

Timing (Temporal Mismatch): One firm may generate waste continuously (e.g., a power plant producing heat), while the receiving firm has seasonal or fluctuating demand, or it operates in batches.

Quantity (Volume Mismatch): The generator may produce insufficient volume to justify the setup costs for the receiver, or conversely, produce too much, overwhelming the receiver's storage capacity.

Location (Spatial Mismatch): Even if the materials match, the transport costs between the two facilities may exceed the value of the recovered material, especially for low-value, high-volume waste/by-product streams.

Operational challenges of Industrial Symbiosis

The "Matching" Problem
(Supply vs. Demand Mismatches)

Quality Variability and Uncertainty

Inventory and Storage Logistics

Information Asymmetry and Trust

Interference with Core Processes

In Lean philosophy, variability (*Mura*) is a major source of waste.
In IS, waste streams are inherently variable in composition, moisture, and purity, which poses a high risk to operations (Simboli et al., 2014, (Lawal et al., 2020).

Process Stability: The main obstacle to the reuse of waste is the uncertainty of its quality. If a byproduct's chemical composition fluctuates, it can damage the receiving firm's machinery or lower the quality of their final product.

Standardization: Unlike virgin raw materials that come with a guarantee of specification, waste streams often lack standardization, requiring the implementation of rigorous Quality Assurance protocols at the source.

Operational challenges of Industrial Symbiosis

The "Matching" Problem
(Supply vs. Demand Mismatches)

Quality Variability and Uncertainty

Inventory and Storage Logistics

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Interference with Core Processes

To buffer against the mismatches in timing and quantity, firms must hold inventory. However, holding "waste" inventory contradicts Lean principles (specifically JIT) and consumes valuable space and capital.

Buffer Management: Material flow optimization requires sophisticated planning to determine the minimum safe buffer stock needed to synchronize the generator and user without incurring excessive holding costs. (Cimren et al., 2011).

Operational challenges of Industrial Symbiosis

The "Matching" Problem (Supply vs. Demand Mismatches)

Quality Variability and Uncertainty

Inventory and Storage Logistics

Information Asymmetry and Trust

Interference with Core Processes

Operational collaboration requires a high degree of transparency, which is often lacking between independent firms (Herczeg et al., 2017).

Operational Risk: The receiving firm faces the risk that the supply might stop abruptly if the generator changes their core process or closes down. This dependency creates a reluctance to invest in the necessary retrofitting technology.

Joint Knowledge Creation: There is often a lack of shared operational data. Without "open-book" transparency regarding the waste's composition and generation schedule, partners cannot effectively plan their production, leading to high transaction costs.

Operational challenges of Industrial Symbiosis

The "Matching" Problem
(Supply vs. Demand Mismatches)

Quality Variability and Uncertainty

Inventory and Storage Logistics

Information Asymmetry and Trust

Interference with Core Processes

Implementing IS can sometimes negatively impact the efficiency of the main production line.

Process Efficiency: If the management of waste sorting and exchange becomes too complex, it can distract from core value-creation activities. The transaction costs associated with managing these peripheral flows can render the symbiosis economically unviable if not managed through efficient Lean processes.

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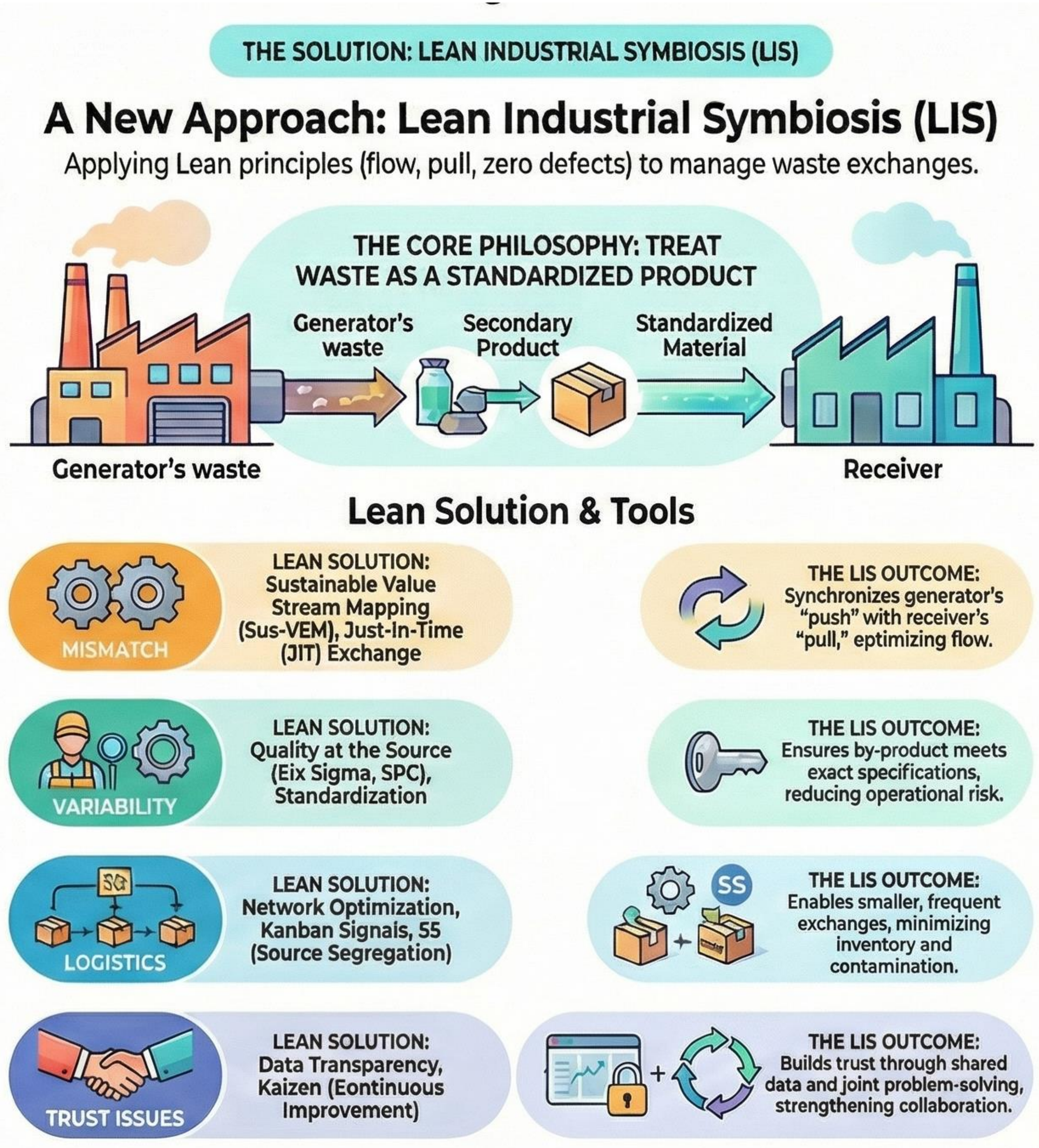

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How Lean and Quality concepts solve the challenges

Lean and Quality methodologies address the operational challenges of IS by transforming undefined **"waste"** into standardized **"products"** and by stabilizing the flow of materials between firms. Some approaches:

- Addressing variability through Standardization and Quality Assurance
- Solving the "Matching Problem" with visual management and flow
- Preventing contamination via source segregation (e.g., 5S)
- Building trust through data and continuous improvement
- Integrating IS into core strategy (C-Lean)

How Lean and Quality concepts solve the challenges

Addressing variability through Standardization and Quality Assurance

Solving the "Matching Problem" with visual management and flow

Preventing contamination via source segregation (e.g., 5S)

Building trust through data and continuous improvement

Integrating IS into core strategy (C-Lean)

The primary barrier to IS is the risk associated with variable waste streams. Lean Quality tools convert risky "waste" into reliable "inputs."

Treating Waste as a Product: To solve the uncertainty problem, the waste generator must adopt an "Eco-Efficiency" perspective, viewing waste not as a liability but as a resource that hasn't found a user yet. This mindset shift necessitates applying the same Quality Assurance standards to waste as are applied to finished goods.

Reducing *Mura* (Variability): By applying Six Sigma or similar process control methodologies to the waste generation process, firms can reduce the deviation in the chemical or physical properties of the byproduct. This standardization ensures the material meets the strict specifications of the receiving firm.
(Simboli et al., 2014; Lawal et al., 2020).

How Lean and Quality concepts solve the challenges

Addressing variability through Standardization and Quality Assurance

Solving the "Matching Problem" with visual management and flow

Preventing contamination via source segregation (e.g., 5S)

Building trust through data and continuous improvement

Integrating IS into core strategy (C-Lean)

Lean tools designed to visualize and optimize flow are essential for synchronizing the supply and demand between two different companies.

Sustainable Value Stream Mapping (Sus-VSM): Traditional VSM helps identify waste; Sus-VSM extends this by visualizing material loss, water, and energy flows alongside time data. This allows managers to quantify exactly *where* and *when* a waste stream is generated, providing the data needed to match it with a partner's demand cycle. (Faulkner & Badurdeen, 2014).

Network Optimization: Just as Lean uses *Heijunka* (leveling) to smooth production, IS networks can use mathematical optimization models to synchronize the "push" of waste with the "pull" of demand. This minimizes the need for large buffers and optimizes transport routes, and can solve the spatial and temporal mismatches.

How Lean and Quality concepts solve the challenges

Addressing variability through Standardization and Quality Assurance

Solving the "Matching Problem" with visual management and flow

Preventing contamination via source segregation (e.g., 5S)

Building trust through data and continuous improvement

Integrating IS into core strategy (C-Lean)

A major operational challenge is that waste is often mixed (e.g., metal shavings mixed with oil), making it useless for high-value recycling.

The Lean & Green Model: By applying 5S (Sort, Set in order, Shine, Standardize, Sustain) at the production level, operators segregate waste immediately at the source. This "source segregation" prevents contamination to ensure the byproduct remains high-quality and valuable for the partner.

Visual Management: Using color-coded bins and clear signage ensures that waste handling is disciplined. This reduces the "transaction costs" of sorting waste later and makes the symbiosis economically viable. (Pampanelli et al., 2013).

How Lean and Quality concepts solve the challenges

Addressing variability through Standardization and Quality Assurance

Solving the "Matching Problem" with visual management and flow

Preventing contamination via source segregation (e.g., 5S)

Building trust through data and continuous improvement

Integrating IS into core strategy (C-Lean)

The "Information Asymmetry" challenge is resolved by the Lean culture of transparency and data-driven decision-making.

Joint Knowledge Creation: Successful IS requires "supply chain collaboration" where partners share operational data. Lean's emphasis on visual data and transparency helps build the trust required for firms to become dependent on each other's flows. (Herczeg et al., 2017).

Process Discipline for Data: Digital enablers (I.40 tech's, sensors, tracking, DPPs) are needed to manage circular flows (e.g., tracking the lifecycle of a battery). However, technology applied to a bad process just speeds up the mess. Lean ensures the physical flow is logical and streamlined, and the "Digital Twin" of the circular flow is accurate. (Cannas et al., 2025).

How Lean and Quality concepts solve the challenges

Addressing variability through Standardization and Quality Assurance

Solving the "Matching Problem" with visual management and flow

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Integrating IS into core strategy (C-Lean)

To prevent IS from interfering with core processes, it must be integrated into the company's standard management framework.

The C-Lean Framework: This framework aligns Circular Economy goals with Lean tools and can help to make waste recovery a standard part of the daily work "Gemba" rather than a distraction. (Nadeem et al., 2025).

Kaizen (Continuous Improvement): By encouraging operators to suggest improvements for waste reduction and valorization, companies can identify "bottom-up" synergies that management might miss. (Domenech, 2014).

Traditional Lean stops at the factory door. LIS (e.g., via Environmental Value Stream Mapping) is expanded to include the restoration of natural systems.

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Trade-Offs and Tensions between Lean and IS/CE

While Lean and Circular Economy (CE)/Industrial Symbiosis (IS) are largely synergistic, there are some **trade-offs and tensions**, in terms of operational efficiency (Lean) and the requirements for environmental regeneration (CE/IS). (Simboli et al. 2014)

Feature	Lean Goal	Circular/IS Goal	The Conflict
Logistics	Frequent, small batches (JIT)	Minimize CO2 emissions	JIT increases transport frequency & emissions.
Inventory	Zero Inventory (Flow)	Buffer storage for matching	IS requires holding "waste" inventory.
Materials	Standardized, Virgin inputs	Secondary, Recovered inputs	Recycled inputs introduce variability (*Mura*).
Focus	Internal Process Efficiency	Inter-firm Synergy	IS adds transaction costs & dependency risks.
Design	Fast Time-to-Market	Durability & Longevity	Rapid cycles can encourage obsolescence.

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