

Research on the Enhancement of Lean Production Management Capability in Production-oriented Enterprises Empowered by Digital Informatization

Wei Zhang¹, Yexuan Zhu², Jin Wang³, Qingqian Meng^{3,*}, Zhen Tian³,
Ruokun Li¹

¹Shandong New Element Biotechnology Co., Ltd., Jining City, 273100, China

²Harbin Institute of Technology, Weihai, 264209, China

³Qufu New Element Bioengineering Co., Ltd., Jining, 273100, China

*Corresponding author: qgb@neuelementchina.com

Abstract: Production-oriented enterprises face inherent constraints such as information lag, data silos, and decision response delay in the process of implementing lean production management, which limit further improvements in waste identification, synchronization control, and continuous improvement capabilities. Digital informatization, with its technical attributes of data collectability, transmissibility, computability, and closed-loop capability, provides a new technical pathway to overcome the above constraints. This study explores the coupling mechanism between digital informatization and lean production management from a theoretical perspective, analyzes the structural evolution of lean management capabilities driven by digital informatization through information entropy reduction, digital twins, and continuous data flow, and then designs enhancement pathways including optimization of acquisition nodes, heterogeneous data fusion, and construction of decision rules driven by real-time analysis. The study proposes that digital informatization, by reshaping the information flow topology and interface reconstruction, enables lean management capabilities to transition from discrete improvement events to continuous online optimization, thereby forming an adaptive lean production control loop.

Keywords: digital informatization; lean production management; information entropy reduction; digital twins; dynamic scheduling

1. Introduction

Lean production management, as a core methodology for production-oriented enterprises to improve operational efficiency, has its capability boundaries long constrained by the granularity, timeliness, and completeness of information acquisition. Traditional lean tools such as value stream mapping, kanban management, and production leveling often rely on manual sampling and empirical judgment at the execution level, resulting in difficulties in timely identifying hidden waste, excessively long closed-loop cycles for improvement, and knowledge accumulation depending on individual experience. The rapid development of digital informatization provides technical possibilities for reconstructing the information processing capability of production systems; however, the theoretical correlation, mechanism of action, and capability evolution path between digital informatization and lean production management have not yet been systematically elucidated. Therefore, this study has a clear necessity for theoretical construction. On the one hand, it is necessary to clarify how digital informatization, starting from its technical attributes, permeates all levels of the production system to form the underlying support for lean management capabilities. On the other hand, it is necessary to reveal the structural evolution pattern of lean management capabilities driven by digital informatization and to design actionable enhancement pathways. This research helps bridge the theoretical gap between information technology and lean management, providing an analytical framework for production-oriented enterprises to understand and apply digital informatization to empower lean management.

2. Theoretical Coupling Mechanism between Digital Informatization and Lean Production Management

2.1 Technical Attributes of Digital Informatization and Its Penetration Logic into Production Systems

The technical attributes of digital informatization are manifested as data collectability, transmissibility, computability, and closed-loop capability. These attributes reconstruct the organizational mode of manufacturing resources by embedding themselves into the perception layer, transmission layer, and decision-making layer of the production system. Sensors and the industrial Internet of Things convert physical production states into continuous digital signals, thereby making explicit the previously implicit equipment conditions, material flows, and labor consumption, and thus changing the production system's response mode to external disturbances and internal variations. On this basis, digital informatization does not simply superimpose itself onto existing production processes; instead, it gradually penetrates all levels through data links into process control, workstation collaboration, and workshop scheduling, forming a vertical integration from unit equipment to the entire value stream.

A production system, as a typical dissipative structure, relies its operational efficiency on the degree of information order and the timeliness of feedback. Digital informatization, through standardized interfaces and protocols, breaks down the barriers among information silos in traditional production systems, thereby forming a closed-loop information flow among planning, execution, and control. This penetration logic follows a progressive path from the improvement of data acquisition accuracy to the reduction of information entropy, and then to the shortening of decision delay. Specifically, digital informatization transforms experience-dependent on-site management into data-driven real-time monitoring, thus enabling rapid localization of variation sources at the process level. This process does not alter the physical essence of the production system, but it reshapes the topological structure of information flow, providing the underlying information infrastructure for the enhancement of lean production management capabilities^[1].

2.2 Core Dimensions of Lean Production Management Capability and Their Information Dependence Characteristics

The core dimensions of lean production management capability include waste identification capability, process synchronization capability, pull control capability, and continuous improvement capability. Waste identification capability requires the production system to accurately distinguish value-added activities from non-value-added activities, and its effectiveness highly depends on the real-time acquisition of information such as process time, material stagnation, and quality deviations. Process synchronization capability relies on the information analysis of takt time, work-in-process inventory, and bottleneck locations; without real-time and accurate data support, synchronization would degenerate into static planning. Pull control capability takes the kanban system as its typical carrier, and the kanban is essentially an information triggering mechanism, whose operational efficiency directly depends on the accuracy and response speed of information transmission.

The above dimensions collectively exhibit a significant information dependence characteristic, that is, the boundary of lean management capability is defined by the availability and interpretability of information within the production system. Under traditional production environments, information lag, distortion, or absence prevents waste from being perceived in a timely manner, and improvement activities often rely on post-hoc analysis. Digital informatization, by providing high-resolution, low-latency production data streams, transforms lean management capability from discrete improvement events into continuous online optimization. Specifically, the information dependence characteristic manifests as sensitivity to data granularity—coarse-grained information can only identify explicit waste, whereas fine-grained information can reveal hidden waste and its related factors. Therefore, the essence of lean production management capability is a kind of organizational cognitive capability based on information processing, whose enhancement must be premised on the upgrading of information infrastructure.

2.3 Transmission Mechanism and Interface Reconstruction of Lean Management Capability Empowered by Digital Informatization

The empowerment of lean management capability by digital informatization is not a linear

superposition, but rather a nonlinear enhancement achieved through multiple transmission paths. The first transmission path is the variation exposure mechanism brought about by improved information transparency, that is, digital informatization converts hidden fluctuations in the production process into visual indicators, thereby exposing problems originally concealed by inventory or buffers to the management's view, and thus triggering targeted lean improvements. The second transmission path is the response acceleration mechanism brought about by the shortened feedback closed loop; real-time data streams significantly reduce the time constant of the control loop, enabling the production system to respond to external demand with smaller batch sizes and faster takt times, which is precisely the core support for lean production's pursuit of one-piece flow and small-batch production^[2].

Interface reconstruction is a structural outcome of lean management capability empowered by digital informatization, and it is mainly manifested at three levels: the human-machine interface, the process interface, and the planning-execution interface. The human-machine interface transforms from traditional dashboards and paper records to digital dashboards and augmented visualization, enabling operators to simultaneously acquire the status information of their own process and its upstream and downstream processes. The process interface eliminates information asymmetry between adjacent processes through digital information sharing, so that the transmission of pull signals does not need to rely on physical kanban but achieves cross-process synchronization via electronic signals. The planning-execution interface shifts from hierarchical issuance to data alignment, where the production plan and on-site execution are directly connected by an information bus, reducing plan deviation and execution delay. This interface reconstruction process essentially transforms the coordination logic of lean management from manual rules to algorithmic rules, thereby enhancing the system's adaptive capability while maintaining lean principles.

3. Structural Evolution of Lean Production Management Capability Driven by Digital Informatization

3.1 The Capability Transition of Production Waste Identification and Elimination Based on Information Entropy Reduction

The waste in the operation process of a production system is essentially an external manifestation of increased information entropy, that is, information uncertainty among processes leads to material waiting, overproduction, and unnecessary handling. Digital informatization significantly reduces the information entropy value of process states by deploying high-density data acquisition and real-time transmission at each node of the production system. When the state of each piece of equipment and each batch of materials is precisely encoded as digital signals, the non-value-added activities, which are regarded as normal fluctuations in traditional production management, are transformed into quantifiable and locatable explicit anomalies. This process enables waste identification to transition from discrete judgments relying on empirical sampling to continuous monitoring based on full-sample data, and the identification accuracy sinks from the process level to the motion level.

The empowerment of waste elimination capability by information entropy reduction is manifested in two transition mechanisms. First, the low-entropy information environment enables the rapid traceability of variation sources in the production system; for example, a slight deviation in the distribution of process times can be detected within several production takts and attributed to a specific workstation or operating parameter, thereby compressing the response time for waste elimination to a real-time level. Second, the reduction of information entropy reveals the correlations among different types of waste; for instance, the relationship between waiting time and quality defects can be quantitatively analyzed through information-theoretic methods, thus avoiding overall efficiency losses caused by local optimization. This transition means that waste elimination is no longer a one-time improvement project but a normalized capability embedded in the production information flow, whose upper limit is determined by the degree of information order achieved through digital informatization.

3.2 Enhancement Effects of Production Synchronization and Pull Control from the Perspective of Digital Twins

Digital twin technology achieves a leap in production synchronization from offline planning to online simulation by constructing a virtual mirror image of the physical production system. In traditional lean production, synchronization relies on the pre-design of takt time calculation and kanban settings; once the production line is running, adjusting the synchronization parameters requires

interrupting production and recalculating. From the perspective of digital twins, the virtual model maintains real-time data synchronization with the physical system, enabling it to reflect dynamic changes in material flow and equipment status with millisecond-level latency. This allows production synchronization to no longer depend on static takt tables, but to dynamically adjust the operation start time and completion time targets of each process based on real-time simulation results of the current work-in-process distribution and bottleneck locations^[3].

The enhancement effect of pull control is manifested in the fundamental changes in the generation method of kanban signals and the response logic. Traditional physical kanban, constrained by the transmission medium, has a low trigger frequency of pull signals and suffers from time lag. The virtual kanban system in a digital twin environment can predict demand fluctuations in the next several production takts based on the twin model, generating preliminary pull signals in advance. At the same time, digital twins support offline simulation of pull rules, that is, evaluating the system response behavior under different kanban quantities and different batch strategies without interfering with actual production, thereby identifying the optimal pull parameter configuration. This enhancement effect transforms pull control from passive inventory triggering into active takt adjustment, improving the buffer capacity against external fluctuations while maintaining low inventory levels.

3.3 The Lean Improvement Closed Loop Driven by Continuous Data Flow and the Knowledge Self-Generation Model

Lean improvement traditionally follows the "Plan-Do-Check-Act" cycle, but information breaks exist between each phase, resulting in long improvement cycles and difficulty in knowledge accumulation. Continuous data flow eliminates these breaks, enabling all stages of the improvement closed loop to operate continuously on the same time baseline. The continuous data flow at the perception layer automatically completes the current situation understanding and problem definition, replacing manual data collection and statistical analysis. The data flow at the execution layer records the implementation process and immediate effects of improvement measures, allowing the judgment of whether the improvement direction is correct without waiting for batch completion. The standardized operations at the action layer are encoded as executable digital rules; once they are verified as effective, they can update the production instruction documents online, achieving a seamless connection from problem identification to countermeasure deployment.

The knowledge self-generation model is a higher-order form of lean improvement capability driven by continuous data flow. In traditional lean improvement, knowledge exists in the experience of technical personnel and in improvement reports, and knowledge transfer relies on interpersonal communication. When continuous data flow accumulates to a sufficient scale, the model can automatically extract association rules between process parameters and performance indicators through machine learning methods. These rules do not depend on preset lean assumptions but autonomously discover waste patterns and improvement opportunities from data distributions. For example, the model may identify that a certain type of product requires additional buffer inventory under specific humidity conditions, or that a particular changeover sequence can reduce average setup time. The self-generated knowledge is stored in digital form and can be transferred across different production lines, thereby shifting lean improvement capability from individual experience dependence to system algorithm driving, and thus breaking through the capacity limits of organizational memory^[4].

4. Design of Enhancement Pathways for Lean Production Management Capability Empowered by Digital Informatization

4.1 Optimization of Digital Information Acquisition Nodes in the Whole Production Process and Improvement of Value Stream Mapping Accuracy

The optimization of digital information acquisition nodes in the whole production process aims to address the fundamental defects of data discreteness and update lag in traditional value stream mapping. Traditional value stream maps are usually drawn based on sampling timing and manual statistics, and their node settings take the process as the smallest unit, thus ignoring non-value-added activities within a process and in the transition areas between processes. Digital informatization allows the reconfiguration of acquisition nodes at a finer granularity, for example, by deploying low-latency sensing devices at key locations such as the starting point of a conveyor belt, the entrance and exit of a buffer zone, and the loading and unloading points of equipment. Through systematic optimization of

the acquisition frequency and data dimensions of these nodes, the waiting time and handling distance, which are smoothed out in the macro value stream map, can be analyzed frame by frame, thereby providing evidence-based baseline data for lean improvement.

The improvement of value stream mapping accuracy is manifested as a dual leap in the time dimension and the space dimension. In the time dimension, continuous data streams replace discrete timing measurements, enabling the statistical distribution characteristics of cycle time, changeover time, and downtime to be fully described rather than only presenting the average value. In the space dimension, the logical relationships among acquisition nodes define the topological structure of material and information flows, and the increase in node density enables the value stream map to locate the specific workstation coordinates where waste occurs, rather than merely the process to which it belongs. This accuracy improvement directly changes the reliability of lean diagnosis—links that might be misjudged as necessary non-value-added activities due to rough data in traditional mapping may reveal pure waste that can be eliminated under fine-grained mapping. The optimization of acquisition nodes and the improvement of mapping accuracy form a positive feedback loop; the former provides the data foundation for the latter, and the latter in turn guides the reconfiguration of nodes^[5].

4.2 The Supporting Architecture of Cross-System Heterogeneous Data Fusion for Kanban Management and Production Leveling

Production-oriented enterprises typically operate multiple heterogeneous information systems, including the manufacturing execution system, the enterprise resource planning system, the warehouse management system, and the programmable logic controller network at the equipment level. These systems differ in data models, timestamp formats, and update frequencies, resulting in the demand signals, inventory status, and capacity information required for kanban management being scattered across different data silos. Cross-system heterogeneous data fusion establishes a unified data middleware layer to align data from different sources according to a uniform material code and time axis. The core of this supporting architecture is to define a set of data mapping rules, so that the real-time status at the equipment level can be associated with the order information at the planning level, thereby eliminating the false triggering or delayed triggering of kanban signals caused by data inconsistencies among systems.

Production leveling requires smoothing the fluctuations in external demand, and its realization depends on a comprehensive judgment of historical demand, work-in-process levels, and process capacity. Heterogeneous data fusion enables the daily-level order forecast from the enterprise resource planning system and the hourly-level actual output from the manufacturing execution system to be compared on the same platform, and the deviation can be detected in real time and trigger leveling adjustments. The fusion architecture also incorporates equipment-level downtime records and quality data into the leveling algorithm, allowing production leveling to take equipment health status into account simultaneously. Kanban management gains a cross-system global view, and the pull signals are generated based on the fused overall production situation, thereby improving robustness against external disturbances.

4.3 Construction of Lean Decision Rules Driven by Real-Time Analysis and the Dynamic Scheduling Response Mechanism

The traditional construction method of lean decision rules relies on the empirical induction of management and engineering technical personnel, and the rule forms are mostly deterministic logics of the "if-then" type, for example, "if the work-in-process exceeds the threshold, then increase the number of kanbans." Such rules are effective in static production environments, but their adaptive boundaries are limited when facing complex scenarios of multi-variety and small-batch production. The rule construction method driven by real-time analysis is based on online data streams, using sliding window statistics and online learning algorithms to continuously evaluate the effectiveness of existing rules under the current production state. When the system detects that the rule performance deviates from the expected interval, it automatically initiates rule revision or the exploration of new rules. This process transforms lean decision-making from a static knowledge base into a dynamically evolving rule system, and the rule update cycle is shortened from the monthly level to the shift level^[6].

The dynamic scheduling response mechanism is the execution channel through which the above rules act on the production system. Traditional scheduling response is characterized by fixed-interval rescheduling, whose time granularity is usually at the daily or shift level, making it difficult to cope

with process-level disturbances. Dynamic scheduling driven by real-time analysis adopts an event-triggered mechanism. When the data stream detects that the actual takt time deviates from the planned takt time beyond the tolerance threshold, or when an unplanned downtime occurs in a certain process, the scheduling engine immediately recalculates the operation sequence and start times of the remaining processes under constraints. This mechanism does not seek the global optimal solution but rather seeks feasible local adjustments that satisfy pull constraints within the framework of lean principles, such as preferentially ensuring the continuous loading of the bottleneck process, or dynamically adjusting the start times of downstream processes to avoid starvation. The dynamic scheduling response mechanism forms a closed loop with the lean decision rules: the rules determine the objective function and constraint boundaries of scheduling, and the performance data of scheduling execution returns to the rule evaluation module, thereby constituting an adaptive lean production control loop.

5. Conclusion

This study constructs a theoretical analysis framework for the enhancement of lean production management capability empowered by digital informatization, reveals the core mechanisms through which digital informatization achieves a transition in waste identification by means of information entropy reduction, enhances synchronization and pull control through digital twins, and drives the improvement closed loop and knowledge self-generation through continuous data flow, and proposes enhancement pathways including acquisition node optimization, heterogeneous data fusion, and decision rules driven by real-time analysis. The research results indicate that the essential role of digital informatization lies in reshaping the information processing structure of the production system, transforming lean management from static rule execution into dynamic adaptive control. Future research directions may include the analysis of boundary conditions for the empowerment effect of digital informatization under different production types, the deep coupling mechanism between digital twin models and lean rule bases, and the application verification of real-time decision-making architectures based on edge computing in distributed production scenarios. In addition, exploring the interpretability of the knowledge self-generation model and the transfer efficiency across different production lines also constitutes an important direction for subsequent research.

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