A New Practice of "Production Line Collaboration + Process Linkage" Optimization Model for Solar Cell Production Lines

Lina Feng[1], Xiaobo Shi[2], Mingyue Sun[3], Zhuan Lin[1], Yaya Zhong[4], Jinkun Dai[1]
[1]College of New Energy Equipment, Zhejiang College of Security Technology, Wenzhou 325000, Zhejiang, China
[2]Hangzhou Hikvision Digital Technology Co., Ltd, Hangzhou 315199, Zhejiang, China
[3]Jinfu Property Service Group Co., Ltd, Hangzhou 310052, Zhejiang, China
[4]Hangzhou Yunchen Technology Co., Ltd, Hangzhou 315199, Zhejiang, China

Corresponding author: Jinkun Dai, fln.2008@163.com

ABSTRACT Driven by the dual-carbon strategic goal, the solar cell industry has developed rapidly, while production efficiency, line balance, and quality control have become increasingly prominent engineering issues. As solar cells convert incident electromagnetic radiation into electrical energy, stable and efficient production-line management is directly related to photovoltaic device performance and clean-energy supply. This paper takes the solar cell production line as the research object and systematically explores an optimization model based on production-line collaboration and process linkage. The development background of the photovoltaic industry and the pain points of traditional production management are reviewed, and the core connotation and theoretical basis of the model are clarified. Implementation paths are proposed from three aspects: cross-process data interconnection, process-cycle matching and bottleneck optimization, and a closed-loop quality traceability system. Practical results show that the model improves the balance rate of the production line, shortens the production cycle, reduces process waiting waste, and supports the transformation of solar cell manufacturing toward digitalization and intelligence. The research provides a reference for high-quality development of photovoltaic and electromagnetic-energy conversion industries.

INDEX TERMS solar cells, process linkage, production line balancing, electromagnetic energy conversion, digital manufacturing

I. INTRODUCTION

Driven by the global trend towards carbon neutrality, the solar photovoltaic (PV) industry has become a major track for clean energy development. According to data from the International Renewable Energy Agency, global PV installations are continuously climbing and are expected to exceed 2800 GW by 2030. China's PV installation scale is also among the world's leading. Solar cells are a crucial component of PV systems, and their production efficiency and quality directly determine the competitiveness of the entire industry chain. However, solar cell manufacturers currently generally suffer from low levels of process automation, unbalanced production lines, and poor inter-process coordination, resulting in low production line balance rates that severely impact capacity utilization. Simultaneously, with the continuous advancement of the "Industry 4.0" and "Made in China 2025" strategies, the digital transformation of manufacturing is accelerating. The solar cell production line also needs to combine lean manufacturing principles with modern information technology to create a new optimization method: a new optimization model of production line collaboration and process linkage.

II. THE CONNOTATION AND BACKGROUND OF THE "PRODUCTION LINE COLLABORATION + PROCESS LINKAGE" OPTIMIZATION MODEL FOR SOLAR CELL PRODUCTION LINES

A. PRODUCTION LINE MANAGEMENT CHALLENGES IN THE CONTEXT OF HIGH-QUALITY DEVELOPMENT IN THE PHOTOVOLTAIC INDUSTRY

by the 3060 dual carbon target, the photovoltaic industry has developed rapidly, and the demand for solar cells has also increased. However, there are also deep-seated contradictions behind the rapid expansion of production capacity, namely, the low degree of automation of production processes, the serious information silos between processes, and the imbalance of production rhythm, which often leads to bottleneck processes, thus affecting the overall capacity utilization [1]. The unstable product yield, high labor costs, and low equipment utilization rate affect each other, which puts great pressure on solar cell companies in the fierce market competition. They urgently need to rely on the improvement of the system production line to achieve both cost reduction and efficiency improvement and quality improvement [2].

B. CORE CONNOTATION AND THEORETICAL BASIS OF THE "PRODUCTION LINE COLLABORATION + PROCESS LINKAGE" OPTIMIZATION MODEL

production line collaboration and process linkage is guided by lean production theory, uses industrial engineering methods as the basic means, and uses industrial Internet of Things technology as digital support to establish a research approach with four levels: macro (overall line layout), qualitative (ECRS and fishbone analysis), quantitative (FlexSim data metrics), and micro (individual operator motions). The digitized data captured through these industrial engineering methods provides the necessary structured input for subsequent big data pattern mining, creating a logic bridge where lean principles define the optimization goals while big data ensures real-time feedback and iterative refinement. Production line collaboration refers to the system coordination between various processes, equipment and links from a global perspective, fundamentally eliminating resource waste [3]. Process linkage focuses on the matching of cycle time and dynamic response between processes, and uses the ECRS principle, 5W1H questioning method and motion economy principle to achieve refined optimization at the process level. The two promote each other and together make the production line shift from local improvement to overall upgrading [4].

C. ANALYSIS OF THE PAIN POINTS AND DRIVING FORCES FOR CHANGE IN TRADITIONAL PRODUCTION MANAGEMENT MODELS

There are three main pain points in the traditional solar cell production line management model. First, the production line balance rate is low, the operation time of each process is different, and the bottleneck process causes a lot of waiting waste [5]. Second, the level of information management is not high, the production line data collection relies on manual labor, the abnormal response is seriously delayed, and rapid decision-making cannot be achieved. Third, the process improvement lacks systematicness, and local optimization that only addresses the symptoms cannot fundamentally solve the problem of production line imbalance. The above problems have prompted enterprises to carry out production management model reform, and rely on the deep integration of lean thinking and digital technology to explore a systematic improvement path that fits the characteristics of solar cell production [6].

III. IMPLEMENTATION PATH AND KEY MEASURES OF THE "PRODUCTION LINE COLLABORATION + PROCESS LINKAGE" OPTIMIZATION MODEL

A. CONSTRUCTION OF A CROSS-PROCESS DATA INTERCONNECTION AND REAL-TIME COLLABORATIVE SCHEDULING MECHANISM

Cross-process data interoperability lays the foundation for production line collaboration. On the solar cell production line, PLC controllers are used to collect key data such as equipment status and production quantity. Various sensing methods such as sensors, RFID tags, barcodes, and cameras are used to create an industrial Internet of Things data acquisition system with sensing, transmission, and application layers. Wired and wireless networks are used to transmit workshop data together [7]. On this basis, the B/S architecture production line real-time monitoring platform is used to connect with the MES system to create a dual-line real-time monitoring system for production plan execution progress and operator task completion progress. The main indicators such as production line balance rate, production cycle, actual working hours of processes, and standard operating time are summarized using data dashboards. Managers can understand the status of the production line at any time, and then coordinate and allocate resources across processes to achieve optimal resource allocation, eliminate information barriers, and continuously improve the overall level of collaboration [8]. In order to intuitively present the sensing means and transmission methods adopted by each level of the industrial Internet of Things, this paper systematically sorts out the core components of the data acquisition system, as shown in Table 1.

B. OPTIMIZATION STRATEGY FOR PROCESS CYCLE MATCHING AND DYNAMIC LINKAGE OF BOTTLENECK PROCESSES

Matching the cycle time of the process is the main link to solve the imbalance of the production line. Under the guidance of lean thinking, the FlexSim simulation software is used to model the solar cell production line in three dimensions. The model incorporates 12 primary workstations, with process service times following a Normal distribution based on empirical workshop data. To ensure statistical reliability, the simulation was configured for a runtime of 480 continuous minutes (one full shift) across 30 independent replications. This setup establishes the correspondence between production line elements and physical objects, using the simulation to obtain data such as the processing rate, idle rate, and equipment utilization rate of each process to accurately find the location and cause of the bottleneck process [9]. Through a combination of qualitative and quantitative methods, on the basis of data analysis, the fishbone diagram analysis method is used to qualitatively find the causes affecting the balance of the production line from several aspects such as people, machines, materials, methods and environment. Then, the 5W1H question method is used to determine the processes that can be improved, and the

TABLE 1. Composition of Industrial Internet of Things Data Acquisition System for Solar Cell Production Line

Level	Perception methods	Transmission method	Main uses
Perception layer	PLC, sensors, RFID, barcodes, cameras	–	Collect equipment status, production quantity, and product identification.
Transport layer	–	Wired network + wireless network	Workshop data is uploaded to the application layer in real time.
Application layer	–	B/S architecture platform integrates with MES	Production monitoring, data dashboards, and collaborative scheduling.

ECRS analysis method is used to cancel, merge, rearrange and simplify the process flow. Combined with the principle of motion economy, the operation mode is optimized from the micro level, and finally the operation time of each process is highly matched with the production cycle time. The whole-link optimization is completed from the whole to the part, and the balance index of the production line is significantly improved [10].

C. ESTABLISHMENT OF A QUALITY TRACEABILITY CLOSED-LOOP SYSTEM AND A RAPID RESPONSE MECHANISM FOR ABNORMAL PROCESSES

The quality traceability closed-loop system is the main support for ensuring product quality stability. In the process of solar cell production, the industrial Internet of Things is used to collect production process data of each process in real time, such as equipment status, failure rate, actual processing time of each process and product quality inspection data, and store the historical data of the whole chain into the platform system, and use big data to realize traceability analysis and pattern mining [11]. On this basis, the production line balance index early warning rules and alarm mechanism are established. When the operation time deviation of a certain process exceeds the set threshold, the system will issue an early warning prompt. Managers can obtain abnormal information through PC or APP mobile terminal as soon as possible, quickly find the problem process and start the rapid response program. Relying on the closed-loop feedback mechanism, the parameters are continuously corrected and optimized, thereby achieving the purpose of improving the balance of the production line, and making the solar cell production line develop towards digitalization, informatization, networking and intelligence [12]. In order to explain the early warning threshold setting and response level classification of key quality indicators of each process, this paper sorts out the core parameters of the platform alarm mechanism, as shown in Table 3.

IV. INNOVATIVE INSIGHTS OF THE “PRODUCTION LINE COLLABORATION + PROCESS LINKAGE” OPTIMIZATION MODEL

To clearly present the effect transmission logic of the ’production line collaboration + process linkage’ optimization model, the relationship between each key measure and the final result is sorted out, and the optimization effect logic diagram is drawn as follows.

A. QUANTITATIVE RESULTS OF IMPROVED PRODUCTION CAPACITY AND YIELD

After the optimization mode of production line collaboration and process linkage is realized, it has produced obvious effects of improving production capacity efficiency and yield. Using FlexSim simulation modeling and IE method to optimize the production line, the production line balance rate reaches more than 90%, the production cycle is reduced by more than 50%, the smoothness coefficient is reduced by more than 70%, and the waiting waste between processes is greatly reduced. Starting from the specific practice of FlexSim modeling of solar cell production line, the standard operating time of each process is accurately obtained by drawing process flow diagrams and process flow diagrams. Different optimization schemes are simulated in the virtual simulation environment. To ensure model validity, the simulation outputs were compared with historical production data from the actual solar cell line. The model was calibrated until the deviation in equipment utilization rates and daily throughput between the simulation and reality was less than 3%, confirming the model’s accuracy before exploring improvement paths. This avoids the trial and error risk and time cost brought about by physical modification [13]. The simulation data clearly shows the difference in the processing rate and idle rate of each station before and after optimization. The load of the bottleneck process is significantly reduced, and the operating efficiency of the entire production line reaches a new height. In terms of product quality, due to the combined effect of process linkage mechanism and abnormal response mechanism, the abnormal working conditions that occur in the production process are intervened in a timely manner. Based on a sample size of 5,000 units collected over a three-month observation period, the baseline scrap rate was reduced from 5.2% to 4.6%, representing a relative reduction of more than 10% ($p < 0.05$). Consequently, the yield rate is steadily improved. Labor consumption is reduced by more than 30%, production cycle is shortened by more than 40%, staffing is more reasonable, and the workload of employees is reduced [14]. In order to intuitively show the improvement effect of the optimization mode on the core operation indicators of the production line, the key indicators before and after optimization are visualized and compared as follows.

TABLE 2. Comparison of cycle time before and after optimization of main processes in solar cell production line

Process	Previous cycle time (s)	Optimized cycle time (s)	Decrease	Main measures
Velvet cleaning	120	105	↓12.5%	Adjust cleaning concentration and optimize carrier loading to match downstream rhythm.
Diffusion sintering	180	108	↓40%	Optimize furnace tube temperature profile and shorten propulsion time to align with the global takt time.
PECVD coating	240	144	↓40%	Rearrange the coating process to improve equipment utilization.
Screen printing	90	54	↓40%	ECRS simplifies screen changing and optimizes printing speed.
Sintering test	150	90	↓40%	Adjusting the sintering curve and conducting parallel testing at each station.

TABLE 3. Quality Early Warning Index System and Response Mechanism for Solar Cell Production Lines

Early warning indicators	Normal threshold	Warning Level	Triggering conditions	Response measures
Process operation time deviation	$\leq \pm 5\%$	Level II Warning	Deviation 5%–15%	The system pushed a notification, and the class monitor confirmed the action.
Process operation time deviation	$\leq \pm 5\%$	Level 1 warning	Deviation $>15\%$	Automatic line shutdown, real-time alerts from management app.
Equipment failure rate	$\leq 2\%$	Level II Warning	2%–5%	Maintenance personnel arrived for inspection.
Product yield	$\geq 98\%$	Level 1 warning	$<95\%$	Initiate quality traceability and suspend shipments.
Production line balance rate	$\geq 90\%$	Monitoring indicators	$<85\%$	Triggering process linkage optimization process.

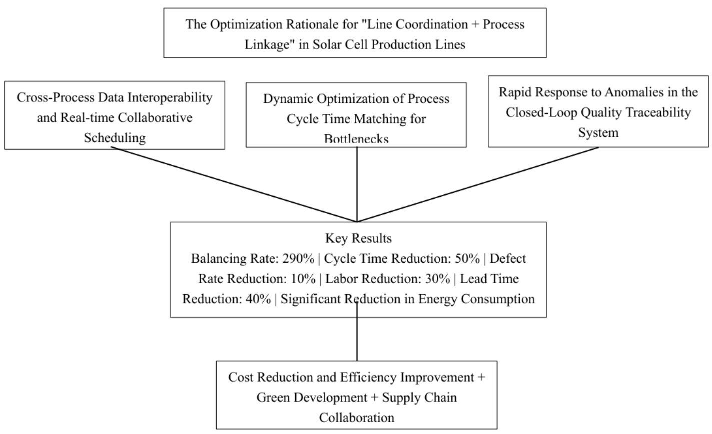

FIGURE 1. Logic diagram of the optimization effect of “production line collaboration + process linkage” in solar cell production line

B. SYNERGISTIC ACHIEVEMENT OF COST REDUCTION AND EFFICIENCY IMPROVEMENT WITH GREEN AND LOW-CARBON GOALS

production line collaboration and process linkage model not only improves production efficiency but also effectively enables solar cell companies to reduce costs, increase efficiency, and achieve their green development goals. From a cost control perspective, improved process linkage reduces waste in various aspects such as ineffective waiting, repetitive operations, and material backlog, thereby directly lowering production and operating costs. Reasonable reductions in labor input and continuous improvements in equipment utilization lower the unit production cost, enhancing the price competitiveness of enterprises in the photovoltaic market. From the perspective of solar power plant installation projects, solar cells are the main component of photovoltaic power generation systems, and their quality stability and consistency are closely related to the power plant’s power generation efficiency and operation and maintenance costs. The production line collaboration and process linkage model ensures continuous and stable

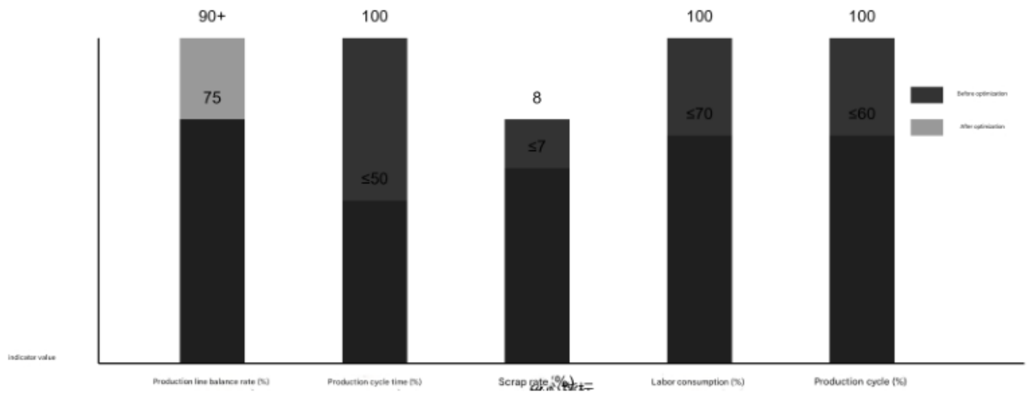

FIGURE 2. Comparison of core indicators before and after optimization of solar cell production line

improvement in product quality. An increased proportion of high-quality battery modules means stronger product quality assurance at the power plant installation stage, reducing operation and maintenance costs caused by module quality fluctuations from the source, extending the power plant's lifespan, improving the overall life-cycle power generation efficiency, and forming a synergistic effect across the value chain from manufacturing to application. In terms of green and low-carbon development, the energy savings brought about by production line balancing optimization should not be underestimated. After the waste of waiting between processes is reduced, the idle time of equipment is reduced, and the energy consumption per unit output value is also reduced, which is in line with the general trend of green transformation of manufacturing under the dual carbon target [15].

C. THE VALUE OF MODEL PROMOTION AND ITS IMPLICATIONS FOR INNOVATIVE DEVELOPMENT IN THE SOLAR CELL INDUSTRY

production line collaboration and process linkage, after its successful application in solar cell production lines, has demonstrated widespread applicability and provided significant insights for the innovative development of the entire industry. In terms of its promotional value, this model, based on lean production theory, integrates FlexSim simulation modeling, IE engineering methods, and Industrial Internet of Things (IIoT) technology to create a complete closed-loop system encompassing "modeling analysis, optimization improvement, and real-time monitoring." It boasts strong systematicity, operability, and replicability. The FlexSim modeling method for solar cell production lines is a relatively novel application exploration in the domestic and international solar cell production research field. It utilizes simulation technology to quickly identify production bottlenecks and verifies optimization effects in a software environment, significantly reducing the risks and resource investment associated with physical trial-and-error in production line transformation. This provides low-cost, high-efficiency methodological support for large-scale industry promotion and has broad application prospects. From the innovative development of the solar cell industry, we can conclude that digital transformation is an inevitable path for improving quality and efficiency. Dynamic websites and mobile applications based on a B/S architecture can achieve traceability and monitoring and early warning throughout the entire solar cell production process. This is a typical model for the informatization upgrade of the manufacturing industry and is of reference value to photovoltaic enterprises of different sizes and technological levels. Secondly, production line optimization must be carried out in collaboration with the entire industry chain. Improving the efficiency of solar cell production lines is not only a matter of the enterprise's own interests, but also ensures a stable supply of high-quality products to downstream solar power plant installation projects, promoting standardized progress and cost reduction in operation and maintenance. This fosters a positive interaction between the manufacturing and power generation sides, achieving an overall improvement in the efficiency of the industry chain. Thirdly, industry revitalization requires the integration of lean manufacturing concepts and technological innovation.

V. CONCLUSION

The innovative practice of production line collaboration and process linkage optimization in solar cell production lines represents a beneficial exploration of the deep integration of lean manufacturing concepts and digital technologies. Research results show that establishing a cross-process data exchange system, a process cycle time alignment and linkage improvement mechanism, and a quality traceability closed-loop response system can significantly improve the balance of the production line, reduce production cycle time and scrap rate, thereby achieving the unified goals of cost reduction, efficiency improvement, and green development. At a time of "dual carbon" goals and the rapid development of the photovoltaic industry, this optimization model provides a systematic and replicable practical solution for the transformation and upgrading of the solar cell industry, possessing significant theoretical and practical value, and should be vigorously promoted and thoroughly explored within the industry.

AUTHOR CONTRIBUTIONS

Conceptualization – Lina Feng, Xiaobo Shi, Mingyue Sun, Zhuan Lin, Yaya Zhong and Jinkun Dai; methodology – Lina Feng, Xiaobo Shi, Mingyue Sun, Zhuan Lin, Yaya Zhong and Jinkun Dai; investigation – Lina Feng, Xiaobo Shi, Mingyue Sun, Zhuan Lin, Yaya Zhong and Jinkun Dai; writing-original draft preparation – Lina Feng, Xiaobo Shi, Mingyue Sun, Zhuan Lin, Yaya Zhong and Jinkun Dai. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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