Research on the Classification of Intelligent Precast Girder Yards in Highway Bridge Construction

Yijun Song[1], Pu Zhang[2,*], Zhitao Zhang[1]

[1]Research Institute of Highway, Ministry of Transport, Beijing, 100088, China
[2]Jiaoke Transport Consultants Co., Ltd., Beijing, 100088, China
*Corresponding author: iamsongyj@163.com

Abstract. During the 14th Five-Year Plan period, China's highway construction industry has vigorously promoted a bridge construction mode featuring standardized design, prefabricated production, and assembly-based construction, leading to the development of a number of advanced intelligent precast component production yards and further elevating the industrialization and intelligence level of bridge construction. Taking small box girder precast yards as the research object, this paper examines the current development status and trends of intelligent precast girder yard (IPGY) construction technology in China and abroad, and establishes a classification method and standard for IPGYs from the dimensions of intelligence level, collaboration level, and decision-making capability. The fundamental definition, technical requirements, and functional objectives of each level are clarified, enabling a full-process, multi-dimensional comprehensive evaluation of IPGYs and providing a unified technical reference for the hierarchical planning, construction, and evaluation of such yards.

Keywords: highway bridge; classification; intelligent precast girder yard; small box girder; intelligent construction

1 Introduction

China has built the world's largest highway infrastructure network. By the end of 2024, the total highway mileage of the country had exceeded 5.49 million kilometers, and the number of highway bridges in service had surpassed 1.1 million. Among these, girder bridges are the most widely used, numbering nearly 910,000 and accounting for more than 80% of all highway bridges in China. Precast girder technology, which employs standardized design and modular construction, is the mainstream approach for constructing girder bridge superstructures, and precast T-girders, small box girders, and segmental girders have long been widely produced using on-site prefabrication methods. In recent years, the deep integration of next-generation information technology, advanced processing equipment, and engineering construction techniques has accelerated the evolution of precast bridge component production toward factory-based, automated, and intelligent processes [1-2]. Intelligent precast girder yards (IPGYs) with increasingly advanced functions and comprehensive systems have emerged in large numbers alongside numerous new construction, renova-

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tion, and expansion projects, driving continuous iteration and upgrading of IPGY construction technology.

A questionnaire survey of 66 key highway construction projects undertaken during the 14th Five-Year Plan period revealed that 31 of these projects had established IPGYs. These yards are primarily concentrated in new construction projects with a high proportion of bridges, as well as in expressway renovation and expansion projects, which require the prefabrication of large quantities of T-girders and box girders. For such projects, the "mass production plus quality control" advantages of IPGYs are significant, and their overall economic benefits have been widely recognized [3].

However, there are significant differences among IPGYs across various projects, yet no unified technical classification standard has been established. Existing research has largely focused on the application of individual technologies or optimization for specific scenarios in IPGYs, while research on the classification of technical systems remains scarce.

In contrast, in the transportation sector, the autonomous driving classification standards have become a unified standard that is widely recognized and implemented both in China and internationally. Technical classification standards have also been gradually developed in specialized fields such as coal mine robots [4], shield tunnel and drill-and-blast tunnel construction [5-6], and smart highways [7-8]. Drawing on the most advanced IPGY construction achievements in the industry to date, and taking a typical precast girder yard for prestressed small box girders as the research subject, this paper proposes a classification standard for IPGYs in conjunction with field survey findings.

2 Basic Definition of Intelligent Precast Girder Yards

The defining feature of an IPGY is its ability to produce precast girders automatically or semi-automatically. In terms of core hardware, unlike traditional precast girder plants, an IPGY employs a controllable mobile production line model, which generally includes fixed tracks laid within the yard, girder-handling equipment (such as mobile formwork and girder transfer trolleys), CNC hydraulic formwork, specialized concrete pouring equipment (feeding and placing equipment), and curing equipment.

In addition to the upgrading of traditional hardware equipment, the integrated application of information technology represents another key technical advantage. By installing appropriate sensing devices, video surveillance equipment, and network infrastructure on site, and by developing a supporting smart management and control system (platform), an IPGY can achieve real-time collection and sharing of production data, as well as monitoring, early warning, and dynamic adjustment. Furthermore, since information technology enables intelligent production scheduling and control, it accelerates equipment turnover and maximizes resource utilization, further enhancing production efficiency. This facilitates the intensive prefabrication of beam and slab components, allowing the IPGY to operate on a factory-like production model. Building on the aforementioned capabilities, implement an integrated layout and optimize process flows for smart manufacturing, deploy more advanced and intelli-

gent machining equipment and data acquisition and control systems, and utilize artificial intelligence for decision-support management. This will enable real-time data exchange among production equipment, decision-making systems, and building information models, ultimately evolving into a nearly unmanned intelligent factory.

3 Current Status of Intelligent Precast Girder Yards

During the 14th Five-Year Plan period, the national government and the industry have vigorously promoted the development of smart construction technologies. Many regions have explicitly set forth requirements such as "intelligent production of prefabricated components" and "building smart beam yards," and IPGYs have gradually evolved from the exploratory stage to widespread adoption. Highway IPGYs primarily adopt a production line model combined with layouts for different process zones, maximizing time efficiency through spatial optimization. [9]

3.1 Comparison of Technology and Equipment Configurations

The construction of an IPGY must comprehensively account for factors such as land availability, transportation conditions, project schedule, and the required quantity of girders and slabs, and should involve a comprehensive assessment of both quality and economic benefits. By comparison, large-scale highway construction projects have certain advantages; the smart girder yards built as part of these projects generally represent the current state-of-the-art in China and are worthy of study and emulation.

This study compares implementation of IPGYs—a common feature across four major projects (the Shenzhen–Zhongshan Link [10-11], the Huangmaohai Cross-Sea Channel, the Sichuan Chengdu–Mianyang Expressway Expansion Project, and the Shiziyang Channel)—as well as in some smaller-scale projects, see Table 1.

Table 1. Comparison of Technical Characteristics of Typical Intelligent Precast Girder Yards

Process/ Equipment	Huangmaohai Cross-Sea Channel	Chengdu-Mianyang Expressway Expansion Project	Shenzhen-Zhongshan Link	Shiziyang Channel	Standard General-Purpose IPGY
Reinforcement Components Production	CNC Machining Equipment Clamping and Forming Jig	CNC Machining Equipment Clamping and Forming Jig	CNC Machining Equipment Clamping and Forming Jig	Top Slab Rebar Production Line Bottom Web Rebar Production Line	CNC Machining Equipment
Formwork Systems	Intelligent Hydraulic Side Forms Retractable Inner Forms Movable Bottom Forms	Intelligent Hydraulic Side Forms Retractable Inner Forms Movable Bottom Forms	Movable Outer Formwork Automatically Retractable Inner Formwork Fixed Bottom Formwork	Fully Automatic Hydraulic Formwork Adjustment System Movable Bottom Formwork	CNC Hydraulic Formwork Fixed Bottom Formwork
Concrete Pouring	Gantry Crane +	Torpedo Tank +	Concrete Pump +	Torpedo Tank +	Gantry Crane +

Process/ Equipment	Huangmaohai Cross-Sea Channel	Chengdu-Mianyang Expressway Expansion Project	Shenzhen-Zhongshan Link	Shiziyang Channel	Standard General-Purpose IPGY
	Hopper Intelligent Attached Vibrators	Placer Intelligent Attached Vibrators	Placing Boom Intelligent Attached Vibrators Self-Propelled Vibration Trolley	Placer Intelligent Attached Vibrators	Hopper CNC-Attached Vibrators
Concrete Curing	Intelligent Temperature- and Humidity-Controlled Steam Curing Intelligent Spray Curing	Intelligent Temperature- and Humidity-Controlled Steam Curing	Intelligent Spray Curing	Intelligent Temperature- and Humidity-Controlled Steam Curing	Intelligent Spray Curing
Prestressing	Intelligent Tensioning and Grouting Equipment	Intelligent Tensioning Robot Intelligent Grouting Equipment	Intelligent Tensioning and Grouting Equipment	Intelligent Tensioning and Grouting Equipment	Intelligent Tensioning and Grouting Equipment
Transfer Equipment	Girder Lifting by Gantry Crane	Girder Lifting by Gantry Crane	Intelligent Girder Transfer Equipment	Rebar Cage Transfer on the Bottom Formwork Girder Lifting by Gantry Crane	Girder Lifting by Gantry Crane
Management System/Features	BIM Management Platform AI-Based Video Process Recognition Digital Formwork Monitoring	BIM Construction Management Platform ERP System Digital Testing Lab BIM+GIS System EBS+WBS Data Traceability	Intelligent Material Handling System Intelligent Production Scheduling System Personnel Management System	BIM Model MES System ERP System SCADA System	Information Management Platform Automatic Data Transfer Online Data Management

3.2 Key Processes and Core Configurations

(1) Reinforcement processing and formwork assembly. Reinforcement processing typically involves optimizing the design of reinforcement components using BIM technology, employing automated nesting software to perform automated reinforcement nesting, and equipping production areas with automated CNC reinforcement processing equipment. Regarding “technologies that can be implemented for precast highway bridge components in the next 3–5 years,” 50 of the 66 key highway projects surveyed believed that “automated integrated forming technology for reinforced steel frameworks” could be implemented first. Existing projects have already adopted

technologies such as visual scanning, intelligent welding robots, and tying manipulators to achieve semi-automatic or fully automatic intelligent forming of top slab and bottom web rebar components. However, these components still require assembly and forming, which places higher demands on the precision of assembly positioning, automatic welding, or tying. Manual intervention is still required when rebar intersections do not align closely or when irregular joints are present. According to statistics on the current status of CNC processing in rebar production at IPGY[12], the coverage rate of general-purpose CNC equipment stands at 58%, through assembly-line-style integration, the automation rate could reach 80%. The IPGY on the Sichuan Riverside Expressway [13] has achieved integrated molding of reinforced components, requiring only 3-4 workers for auxiliary operations, with an automation rate of over 90%. However, the automated positioning and installation of prestressing ducts, anchor plates, and other components have not yet been realized. Further integration of technologies such as BIM, the Internet of Things, visual recognition, and cloud computing is needed to achieve fully automated production with virtually no human intervention.

(2) Concrete pouring. Concrete pouring primarily involves the formwork system, the concrete conveying and placing system, and the compaction system.

1) Bottom formwork and track system. Formwork platforms are installed at the concrete pouring stations; common types include mobile and fixed platforms. The mobile workstation moves along embedded tracks laid out on-site and, when combined with the bottom formwork, forms a mobile bottom formwork system that enables automatic transport from the rebar processing area to the production line. Some projects have also developed automatic rebar cage transport vehicles. Most projects use automated gantry cranes to lift finished beams, while the Shenzhen-Zhongshan Link project has developed a beam transfer trolley, which has largely automated the process of moving beams to the storage area. However, overall, transfer operations are still predominantly performed manually or via automated operation along short, predefined routes. The positioning and gripping of components, automated transfer, and storage systems will be the future direction for fully automated smart beam yards IPGYs.

2) Hydraulic side forms and inner forms. Mobile formwork stations are equipped with fixed hydraulic side forms, while fixed bottom formwork stations utilize mobile hydraulic side forms. By comparison, mobile formwork stations eliminate the need for hoisting between processes and long-term site occupation, making them more conducive to space saving and assembly-line production. The inner forms employ a fully automated hydraulic adjustment system and are automatically retracted upon completion of concrete pouring. The Shiziyang Channel project introduced an innovative fully automated hydraulic formwork adjustment system capable of adapting to more complex structural cross-sections. Formwork cleaning after demolding typically involves manual cleaning and the spraying of release agents; however, an integrated automatic formwork cleaning and spraying device has now been developed, capable of performing unmanned operations such as sanding, polishing, dust removal, and spray painting of molds, while improving the quality of formwork grinding and the uniformity of release agent application [14].

3) Compaction equipment. Concrete compaction primarily employs formwork-mounted vibrators attached to the side forms, as well as insert vibrators. The Shenzhen–Zhongshan Link developed a self-propelled top slab compaction trolley equipped with multiple vibrators that can be remotely controlled for insertion and withdrawal, moving longitudinally along tracks mounted on top of the side forms.

Current developments in intelligent vibration technology focus primarily on insert vibrators and generally concentrate on three aspects: compaction monitoring, vibration position and status monitoring, and automated insertion and withdrawal [15]. The integration of vibrating equipment with the concrete placement system and formwork system enables fully automated vibration operations.

4) Pouring equipment. In addition to conventional concrete mixer truck pumping, both the Chengdu–Mianyang Expressway Expansion Project and the Shiziyang Channel Project have installed torpedo-tank material transport systems above the production lines. The torpedo tanks travel on rails to overhead placing booms, which then distribute the concrete. Sensors installed on the equipment monitor the condition of the concrete in real time and make dynamic adjustments. This system makes full use of the overhead space but presents challenges such as stringent positioning requirements and limited recovery of residual concrete from the tanks; these issues have now been largely resolved through technical improvements.

(3) Concrete curing. Since production lines require high equipment turnover rates, intelligent temperature- and humidity-controlled curing kilns (chambers) are generally used. Steam curing is employed to enhance the early strength of concrete and improve curing efficiency, and high-temperature steam curing is currently performed automatically based on preset temperature, humidity, and duration parameters. In the girder storage area, spray curing systems with preset parameters are commonly used for secondary curing. Currently, some projects have implemented intelligent spray curing under dynamic monitoring by installing temperature and humidity sensors.

(4) Prestressing tensioning. Intelligent tensioning and intelligent cyclic grouting equipment are now widely used. Intelligent tensioning equipment employs dual control of tensioning force and elongation, while intelligent grouting equipment adopts vacuum-assisted grouting to improve grouting quality. The Chengdu–Mianyang Expressway Expansion Project has adopted multi-arm tensioning robots capable of synchronous tensioning of multiple strands. However, processes such as anchor plate and anchorage installation, as well as anchor sealing, are still performed primarily manually. Furthermore, grout density is often tested manually after construction using the impact-echo method [16], and precise in-process monitoring and post-construction inspection technologies remain lacking.

(5) Inspection technology. Quality inspection of finished girders is still conducted largely manually, primarily due to the lag in the development of intelligent inspection technologies. While some projects have adopted 3D laser scanning, machine vision, and image recognition technologies for dimensional [17] and visual appearance inspections, such as: the average accuracy rate for rebar quantity inspection is 98.1%, for dimensional inspection reaches 69%, for spacing inspection reaches 95%; machine vision accuracy can reach 100%, and the accuracy rate for rebar spacing inspection also reaches 90%. However, there are still no intelligent solutions for inspecting indi-

cators such as strength and post-construction cover thickness. Inspection accuracy directly impacts intelligent decision-making and production. For automated production that relies on manual verification and decision-making, 100% automated inspection of pre-processing metrics and an average accuracy rate of at least 90% are sufficient to meet requirements;

(6) Smart control and management platform. A management system (platform) that integrates multiple functions and enables collaborative management is one of the key components of an IPGY [18]. In addition to integrating basic management functions such as quality, safety, schedule, and documentation, the smart control and management platform typically uses BIM technology to create models of the site technical layout, temporary facilities, and beam-and-slab structures for clash detection and construction simulation [19-21]. By establishing a network communication infrastructure and installing smart sensors, the platform collects production data from equipment and laboratory test results and integrates them with production control systems for collaborative management. The IPGY of the Huangmaohai Cross-Sea Channel incorporates AI-based process recognition, while the Chengdu–Mianyang Expressway Expansion Project uses EBS and WBS structure trees to correspond with subprojects and sub-items, enabling dynamic updates of production information.

IPGYs have all developed strong sensing capabilities, but they are not yet capable of highly automated, collaborative operations throughout the entire process; there is still significant room for improvement in AI-based autonomous learning, analysis, assessment, and decision-making.

4 Classification Methods and Standards for Intelligent Precast Girder Yards

4.1 Classification Methods and Factors

Research on technical classification methods and standards in the field of highway construction is currently limited. For shield tunneling technology, classification is based solely on the level of intelligence, while similar studies in other fields adopt the functional objectives that the technology can achieve as the classification criterion. However, for IPGYs—which involve multi-process equipment, human–machine interaction, and system–equipment interaction—such single-factor classification methods cannot provide effective guidance for their construction. Some regions and projects have proposed developing "IPGY 3.0" or "IPGY 4.0" versions; however, in terms of technical configuration and functionality, these represent merely incremental improvements over the previous generation of IPGYs rather than a fundamental iteration of technical capabilities. Furthermore, given the rapid development of smart construction technologies, industrial equipment, and artificial intelligence, it is difficult to unify equipment and technical configurations into an effective classification standard. Therefore, based on the main processes of precast girder production, a comprehensive evaluation and classification are conducted according to five factors: functional objec-

tives, level of intelligence, level of collaborative operation, decision-making capability, and level of digitalization. The specific elements and details are shown in Table 2.

Table 2. Classification Factors of Intelligent Precast Girder Yards

Classification Criteria	Content
Functional Objectives	Achievable production and management objectives, such as: the production of rebar components, automated forming of rebar frameworks, and the collection of all production process data
Level of Intelligence	The degree of automation and intelligence in the production process, as well as the level of human intervention, are used to classify functional objectives
Level of Collaborative Work	Manner in Which Personnel, Equipment, and Systems Collaborate
Decision-Making Capability	The level of decision-making capability reflected in production and management, such as: manual decision-making based on experience, decision support using AI-based analysis, and AI-driven intelligent decision-making.
Level of Digitalization	BIM-based visualization management, production and design optimization, construction process simulation, digital twins, etc.

In the industrialized construction approach adopted by IPGYs, the production of precast girders must ensure that quality, safety, and efficiency meet the required standards; this is also a fundamental prerequisite for conducting classification evaluation based on the aforementioned classification criteria. Based on current industry developments and trends in technological breakthroughs, the classification of certain quantitative evaluation indicators is shown in Table 3 below.

Table 3. Grading of Selected Quantitative Evaluation Indicators

Indicators	Generally	Latest Developments	Future Outlook
Automation Rate of Rebar Processing	80%	≥95%	100%
Automation Rate for Reinforcement Cage Formation	60%	≥90%	100%
Quality Intelligent Inspection Coverage Rate	80%	90%	100%
Average Accuracy Rate of Intelligent Quality Inspection	-	95%	100%
Formwork Cleaning, Automation Rate for Spray Coating	0%	100%	100%
Automation Rate of Smart Maintenance	80%	90%	100%

4.2 Definition of Classification Levels for Intelligent Precast Girder Yards

Based on the current status and development trends of IPGY construction, a five-level classification system is adopted for IPGYs. The corresponding definitions and typical characteristics of each level are presented in Table 4.

Table 4. Classification Definitions of Intelligent Precast Girder Yards

Classification Level	Definition	Typical Functional Objectives	Collaborative Operation Capability	Decision-Making Capability	Level of Digitalization
L1	Basic Automation	Computerized Management; Standalone Automated Production under Manual Control	No Collaborative Capability	Manual Decision-Making	Basic Data Recording, Storage and Collaborative Management
L2	Basic Intelligence	Automated Production and Control Using Preset Parameters for Key Process Steps	Information Exchange and Collaborative Control Among Personnel, Platforms, and Machines via Sensing Devices	Manual Decision-Making; Basic Equipment Information Collection, Early Emergency Control	Digital Technologies for Design Optimization and the Generation of Manufacturing Parameters
L3	Semi-Intelligent Assembly Line	Assembly-Line Production Model	Some processes are automated and coordinated, while manual intervention is required for certain installation and handling tasks	Decision-making is primarily manual, and equipment controls production based on instructions or schedules.	BIM-Based Forward Design
L4	Smart Assembly Line	1. Automated Forming of Reinforcement Cages; 2. Intelligent Monitoring and Inspection of Key Production Factors and Metrics Throughout the Entire Process	Highly automated coordination among key processes, with human intervention limited to emergency situations only	Human-led decision-making, with equipment providing collaborative sensing and AI technology assisting in decision-making	Real-time Interaction Between Production Data and Digital Models
L5	Near-Unmanned Factory	1. Digital Twin; 2. AI-Powered Decision-Making	Integrated collaboration across design, management, and production, with human intervention in management limited to responding to changes in off-site supply and demand	Intelligent Production Decision-Making, Human-Assisted Decision-Making	BIM Model-Driven Production, Digital Twin

(1) L1: Basic Automation

An information platform has been established, but data collection, transmission, and analysis rely heavily on manual labor, and BIM models are used solely for visualization. In terms of equipment, CNC machines have been installed to enable automated single-machine operations under the supervision of specialized technical personnel. A key characteristic of this approach is that it incorporates information manage-

ment functions and offers semi-automated production capabilities, while requiring a relatively low capital investment.

(2) L2: Basic Intelligence

An automated rebar processing production line and a smart concrete batching plant were constructed to enable automated production based on preset parameters and under manual supervision. BIM technology was applied to design review and manufacturing, and a management platform was built based on the BIM model to integrate production data with the digital model.

(3) L3: Semi-Intelligent Assembly Line

Implement semi-intelligent assembly line production under human supervision, using configured sensors to collect production data and perform automated control, with real-time interaction between production data, BIM models, and management systems. Based on experience gained from multiple projects, it is generally recommended to build this type of IPGY for projects requiring the production of 2,000 or more precast girders. Land area must also be taken into consideration; an IPGY with a production target of 2,000 or more girders typically requires a site area of no less than 100,000 m^2.

(4) L4: Intelligent Assembly Line

It solves the complex processes involved in the automated assembly, welding, and forming-or integrated forming-of reinforced steel framework components; the automation rate exceeds 95%; manual intervention is required only in complex situations such as the intersection of connection nodes, when cumulative errors exceed the threshold, or when making decisions regarding critical processes. The on-site handling of rebar components, concrete, and girders is 100% automated. On this basis, they achieve intelligent production of key processes and a high degree of automated coordination between process steps. As the foundation for digital twins and fully intelligent construction, they enable end-to-end intelligent monitoring and inspection of key production factors and quality indicators. Furthermore, they employ AI, big data, cloud computing, and other technologies to perform intelligent analysis of the production process and provide decision-making support.

(5) L5: Near-Unmanned

Achieving a near-unmanned factory, where AI technology and information platforms enable decision-making and collaborative management of all production operations, with the capability to intelligently sense, collect, and control all production factors within the facility. Integrated collaboration across design, management, and production, with digital models driving equipment production and production data feeding back into the digital models, achieves a “digital twin.” Technical personnel’s decision-making is limited to off-site coordination-such as production scheduling and raw material supply to align with on-site progress-emergency takeovers during unforeseen circumstances, and necessary interventions resulting from changes in processes or designs.

4.3 Classification Standards for Intelligent Precast Girder Yards

The classification of IPGYs is based on the classification criteria and definitions described above and is performed by comprehensively evaluating multiple classification factors. The specific criteria are presented in Table 5.

Table 5. Classification Standards of Intelligent Precast Girder Yards

Item	L1	L2	L3	L4	L5
Site Layout	Reasonable Functional Zoning	Reasonable Functional Zoning	Local Assembly Line Model	Full-Line Production Model	Full-Line Production Model
Digital Technology	Visual Presentation	Production Data Generation	3D Forward Design	Data-Model Interaction	Digital Model-Driven Manufacturing and Digital Twin
Monitoring and Testing	Manual	Monitoring of Equipment Production Parameters	Image- and Scan-Based Quality Identification and Inspection Coverage ≥ 80%	Intelligent Detection of Over 90% of Physical Quality Data Average Detection Accuracy ≥ 95%	100% Intelligent Inspection of Physical Quality Data
Production Decisions	Manual	Manual	Manual Decision-Making with Equipment Emergency Alerts	Primarily manual, with AI-powered analysis to support decision-making	Intelligent Decision-Making: Necessary Human Intervention When External Conditions Change
Reinforcement Fabrication	Manual Machining	Automatic Machining Using Preset Programs Automation rate ≥ 60%	Automatic Machining Using Preset Programs Automation rate ≥ 80%	Automated Processing Based on Collaboration Instructions Automation rate ≥ 95%	Intelligent Production Scheduling/Machining
Reinforcement Component Production	Manual	Automated Wire Mesh Processing; Manual Assembly and Forming Automation rate ≥ 60%	Automated Processing of Reinforcement Components; Manual Assembly and Forming Automation rate ≥ 80%	Automated Assembly and Welding of Reinforcement Cages Automation rate ≥ 90%	Integrated Intelligent Forming of the Entire Reinforcement Cage
Concrete Production	Manual	Automated Production Using Preset Programs	Automated Production Using Preset Programs	Automated Production Based on Collaboration Instructions	Intelligent Scheduling/Production
Concrete Placement	Manual	Manual	Automated Placement via Preset Programs; Manual Assistance	Automated Placement Based on Collaboration Instructions	Intelligent Placement

Item	L1	L2	L3	L4	L5
Concrete Compaction	Manual	Automated Vibration via Preset Programs	Automated Vibration via Preset Programs	Automated Mobile Vibration	Intelligent Monitoring and Control of Vibration
Formwork Installation and Removal	Fixed Formwork; Manual Installation and Removal	Automated Opening/ Closing of Outer Formwork Manual Installation and Removal of Inner Formwork	Automated Installation, Removal, and Travel via Preset Programs	Automated Installation, Removal, and Travel Based on Coordination Instructions	Intelligent Collaborative Control
Formwork Cleaning/Spraying	Manual	Manual	Automated Cleaning/ Spraying via Preset Programs	Automated Cleaning/Spraying Based on Coordination Instructions Automation Rate 100%	Intelligent Collaborative Cleaning/Spraying Automation Rate 100%
Installation of Prestressing Ducts and Anchors	Manual	Manual	Manual	Automated Threading, Positioning, and Installation	Automated Threading, Positioning, and Installation
Prestressing Tensioning and Grouting	Manually Operated CNC Tensioning/ Grouting	Manually Operated CNC Tensioning/ Grouting	Intelligent Tensioning/Grouting with Multiple Preset Parameters	Intelligently Dynamically Controlled Tensioning/ Grouting	Intelligently Dynamically Controlled Tensioning/Grouting
Curing System	Manual	Intelligent Curing via Preset Programs	Intelligent Curing via Preset Programs Automation Rate ≥80%	Monitoring-Based Intelligent Curing Automation Rate ≥90%	Intelligent Collaborative Curing Automation Rate 100%
Transfer and Handling System	Manual	Manual	Automated Transport via Preset Programs	Automated Transport Based on Coordination Instructions	Intelligent Planning and Transportation

IPGYs investments and returns vary by tier. Comprehensive cost estimates are calculated based on the scale of the project, for example, see Formula (1):

$$\mathrm{f}\left(m,n,x\right)=C+M\left(m,\mathrm{n}\right)+T\left(x\right)+V\left(m,n,x,k_i\right)+D \tag{1}$$

where, f represents the benefit-to-cost ratio; C represents construction costs; M represents maintenance costs; T represents transportation costs; V represents cost savings resulting from improved efficiency, which is typically a negative number; D represents demolition costs; for permanent beam yards, D is 0; m represents the duration of operation; n represents the number of production lines; x represents the number of beams required; k_i represents the efficiency improvement factor, which is derived

from factors such as beam production efficiency, reduced labor input, and lower rework costs due to improved quality.

Based on recent trends, Level 1–2 IPGYs are typically suitable for general small- and medium-sized projects, while Level 3 IPGYs are suitable for most major engineering projects today. Due to their high construction and maintenance costs, Level 4 IPGYs are suitable for major projects with extremely high beam production demands or for permanent beam yards with favorable transportation conditions. Level 5 IPGYs, on the other hand, are suitable only for beam manufacturing plants that supply commercial beams.

5 Conclusion and Outlook

By analyzing the application of typical IPGY technologies in China and abroad, as well as trends in the development of intelligent production technologies for precast components, this paper—based on a definition of the fundamental characteristics and construction requirements of IPGYs—has examined the differences in technical and equipment configurations across key processes such as rebar processing, concrete pouring, and prestressing construction, and has proposed a classification standard for IPGYs. Focusing on five core classification factors—functional objectives, level of intelligence, level of collaborative operation, decision-making capability, and level of digitalization—the paper refines the technical requirements for the main prefabrication processes of IPGYs at different levels and establishes a five-tier classification system ranging from L1 to L5, providing a unified reference standard for the classification and evaluation of IPGYs.

With the rapid development of technologies such as artificial intelligence and humanoid robots in China, AI-enabled IPGYs are bound to emerge in the future. This will bring profound transformations to the industrialized construction model and smart production methods of highway bridge construction, shifting production management from a model reliant on human experience to a digital and intelligent management paradigm, and upgrading traditional labor-intensive operations to fully automated robotic operations. IPGYs will gradually establish a systematic management framework for precast production that is "self-adaptive and self-optimizing," thereby achieving safe and efficient unmanned precast production.

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