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Applications of Taguchi Methods in Prestressed Concrete Structures

Jose Antonio Lozano-Galant [1], Carlos Gisbert [2], Ye Xia [3,*], Fidel Lozano-Galant [1,3], Alejandro Mungaray [1]

[1] Dept. of Civil Engineering, University of Castilla-La Mancha, C/ Altagracia, 13071 Ciudad Real, Spain;
[2] Dept. of Civil Engineering, Polytechnical University of Valencia, Camino de Vera, s/n, 46022 Valencia, Spain;
[3] Dept. of Bridge Engineering, Tongji University, Shanghai 200092, China.
* Correspondence: yxia@tongji.edu.cn

Abstract: Prestressed concrete (PSC) structures are fundamental to bridges, buildings, and other critical infrastructure, requiring design approaches that balance mechanical performance, durability, and cost throughout the service life. Because PSC systems involve numerous interacting variables—from material properties to construction practices and long-term environmental effects—their optimization demands methods capable of studying many factors simultaneously and identifying robust combinations. The Taguchi method, a branch of design of experiments (DoE), offers an efficient framework for this purpose, yet its application to PSC remains limited and not well established. This paper addresses that gap by outlining the principal potential applications of the Taguchi methodology throughout the PSC structures life cycle—covering Design and Material Dosage, Production and Prefabrication, Construction and Erection, Service and Operation, and Rehabilitation and End-of-Life stages—highlighting opportunities for future research and practical implementation. Building on this context, an illustrative cost-optimization case study is presented in which a Taguchi orthogonal array is applied to the design of an industrial precast PSC building. In this example, four key design factors—Distance Between Frames, Beam Type, Purlin Type, and Pillar Section—are analyzed to identify the most influential parameters and to determine the configuration that minimizes production and transportation costs. This study encourages researchers to apply Taguchi methods throughout the PSC life cycle.

Keywords: prestressed concrete; orthogonal arrays; taguchi method; precast building; life-cycle applications

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1 Introduction

Prestressed concrete (PSC) structures form a critical part of modern infrastructure, supporting bridges, industrial buildings, transportation systems and many other facilities that demand high load-carrying capacity, long spans, and durability over decades of service. Their attractiveness lies in the synergy between high-strength concrete and prestressing steel, which allows slender members and efficient material use while controlling deflection and cracking. Achieving these benefits, however, requires careful consideration of a wide range of interacting variables whose combined influence governs both immediate performance and long-term reliability. A literature review of the advancements in sustainable prestressed concrete technologies can be found in [1].

The behaviour of PSC systems depends first on the properties of the concrete itself compressive strength, elastic modulus, creep and shrinkage, and resistance to environmental degradation. Equally important is the mix dosage, since the precise proportioning of cement, water, aggregates, and supplementary cementitious materials governs workability, early-age strength development, and long-term durability. The selection and dosage of chemical admixtures, such as superplasticizers, retarders, or air-entraining agents, play a crucial role in controlling setting time, rheology, and resistance to cracking, especially when high-performance or self-compacting concretes are required. The characteristics of the prestressing tendons, including their type, layout, level of prestress, and anchorage configuration, further determine the internal stress distribution and the control of deflections and cracking. Time-dependent phenomena such as creep of concrete, shrinkage, and relaxation of the steel cause progressive losses of prestress that must be predicted accurately to ensure serviceability. Construction procedures add another layer of complexity: curing regime, sequence of tensioning and de-tensioning, temperature and humidity during fabrication, and tolerances in placement can all modify the final stress state and structural behaviour. After construction, environmental actions—daily and seasonal temperature gradients, humidity cycles, and exposure to aggressive agents such as chlorides or sulphates—continue to affect the structure throughout its life span.

These and other numerous variables rarely act in isolation. They interact in non-linear ways, so that the change of one parameter may amplify or mask the effect of another. Because several factors operate simultaneously, it is challenging to identify the specific influence and statistical relevance of each one through traditional "one-factor-at-a-time" experimentation or simple sensitivity studies. A more systematic strategy is needed to capture the combined effects and to rank the parameters that most strongly influence structural performance.

Design of experiments (DoE) offers such a strategy [2,3]. DoE provides a structured approach to planning and analyzing tests so that multiple factors and their interactions can be evaluated efficiently. Instead of varying a single parameter while holding others constant, DoE arranges experiments according to a statistical design that allows independent estimation of main effects and selected interactions with far fewer trials than a full factorial program.

The efficiency and robustness of Taguchi designs have led to their adoption in a wide range of disciplines. They are especially prominent in manufacturing and industrial engineering, where they optimize machining parameters, reduce defects, and enhance product quality (see ref. [4-14]) These and other studies in the literature demonstrate the method's versatility and its ability to deliver statistically reliable results with a fraction of the testing effort required by conventional approaches.

Although the Taguchi method is widely used in other fields, its application to prestressed concrete structures remains scarce. The high initial costs, long construction timelines, and intrinsic complexity of PSC make it an ideal candidate for robust design. Yet the literature offers only scattered studies on Taguchi designs for prestressing parameters, and no comprehensive framework exists for systematic use in design, production, or maintenance. This gap is striking as demand grows for economical, durable, and sustainable prestressed systems.

The present paper aims to help close this gap by illustrating the potential of the Taguchi method for prestressed concrete engineering. It first provides a concise introduction to the fundamentals of the methodology, describing orthogonal arrays, the signal-to-noise concept and the analysis of variance that together form the basis of Taguchi experimental design. It then reviews the main applications of this methodology in civil engineering applications throughout the literature. Next, potential applications of Taguchi method across the life cycle of PSC structures, are presented. To illustrate the practical benefits, a detailed application of the Taguchi approach to the cost-optimized design of an industrial precast PSC building is then presented. In this example, four key design factors are analyzed to identify the most influential parameters and to determine the configuration that minimize both production and transportation costs. Finally, the principal conclusions are drawn, highlighting the insights gained and the opportunities for future research and practice in applying Taguchi methods to prestressed concrete structures.

The remainder of the paper is organized as follows: Section 2 explains the fundamentals of the Taguchi method and its previous applications in civil engineering; Section 3 reviews previous applications of Taguchi method in PSC structures and its potential applications; Section 4 describes the methodology of the proposed case study. Finally, Section 5 presents the main conclusions.

2 Applications of the Taguchi Method in Civil Engineering

This section begins by presenting the fundamental principles of the Taguchi method, explaining its core concepts such as orthogonal arrays, signal-to-noise analysis, and analysis of variance that form the basis of robust experimental design. After establishing this methodological foundation, the discussion moves on to a comprehensive review of the method's main applications within civil engineering, highlighting representative studies from the literature.

2.1 Taguchi Method

Among the many DoE approaches, the Taguchi method has gained special prominence for engineering applications. Developed by Genichi Taguchi[3], this method introduces the concept of robust design, where the objective is not only to optimize mean performance but also to reduce sensitivity to uncontrollable "noise" variables such as environmental fluctuations or material inconsistencies. Central to the method are orthogonal arrays that ensure balanced combinations of factor levels and enable the independent evaluation of each factor's influence, while the signal-to-noise ratio provides a metric that captures both performance and variability.

The Taguchi method is a robust design and quality-engineering technique developed to improve product and process performance while minimizing experimental effort. At its core is the concept of orthogonal arrays (OAs)—carefully constructed experimental matrices in which each column represents a controllable factor and each row represents a single trial. The orthogonality of these arrays ensures that the influence of each factor on the response can be evaluated independently, even when many factors vary simultaneously. This statistical balance allows researchers to isolate main effects and selected interactions with far fewer experiments than a full factorial design, whose size grows exponentially with the number of factors and levels, making the Taguchi method highly attractive for engineering investigations where testing is costly or time-consuming.

A detailed, step-by-step demonstration of how to apply the Taguchi method to an experiment involving three factors, each tested at two levels, is provided by Gisbert et al. [15]. Their work illustrates how to select an appropriate orthogonal array, assign factors and interactions to specific columns, conduct the planned trials to identify the optimal factor settings with minimal experimental effort.

The data generated by an OA are typically evaluated using analysis of variance (ANOVA), which partitions the total response variation into components attributable to individual factors and their interactions. ANOVA provides a percentage contribution for each factor, yielding a quantitative ranking of influence that guides engineers toward the parameters that most strongly affect the outcome and therefore warrant tighter control or further study. This combination of S/N analysis and ANOVA enables both qualitative and quantitative insights without requiring an exhaustive set of experiments.

Implementation of a Taguchi study follows a straightforward sequence: define the problem and select the relevant control factors and levels; choose an appropriate orthogonal array (OA)—designated as Lx, where the "L" indicates a standard Taguchi orthogonal array and the number "x" specifies the total number of experimental runs (e.g., L4 has 4 runs, L9 has 9, L16 has 16)—sized to the number of factors while balancing resolution and experimental cost; conduct the tests or simulations for each trial specified by the OA and record all relevant responses; finally, analyze the data to calculate signal-to-noise (S/N) ratios, perform ANOVA, and confirm the predicted optimum through validation runs or independent simulations. By integrating these steps, the Taguchi method provides a statistically balanced yet practical strategy for exploring multi-factor design spaces.

2.2 Previous Applications in Structure Design

The features of the Taguchi method make this approach particularly suitable for structural engineering, where numerous interacting variables—material properties, geometric parameters, prestressing levels, curing conditions, and environmental influences—must often be considered simultaneously. In prestressed concrete projects, the ability to identify key factors and their interactions with a manageable number of experiments provides a powerful means to enhance reliability, improve decision-making, and design processes that remain stable under the variability inherent to construction and long-term service conditions.

To synthesize the state of the art, Tables 1 to 4 cluster the main applications of the Taguchi method in the structure design field according to four major groups: Concrete Mix Design and Sustainable Materials (Table 1), Structural Elements and Durability (Table 2), Bridge and Viaduct Optimization (Table 3), and Inspection and Monitoring with Unmanned Aerial Vehicles (UAV) (Table 4). Each table reports, by row, a representative study from the literature. The columns are organized to provide: (i) the application where the Taguchi method was used, (ii) the objective pursued by the researchers, (iii) the orthogonal array (L) employed in the experiment, and (iv) other details, such as the number of factors considered and the specific variables analyzed. Finally, each study is linked to its reference number to allow cross-checking with the complete reference list.

Table 1 Previous applications of Taguchi orthogonal arrays in concrete mix design and sustainable materials

Application	Objective	Orthogonal array	No. factors & key factors	Ref.
High-strength concrete (HSC)	Maximize compressive strength and minimize cost	L27	5 factors: water/cement ratio, silica fume %, fly ash %, superplasticizer dosage, curing conditions	[16]
Self-compacting concrete – fresh properties	Optimize slump flow and workability	L18	6 factors: cement content, fly ash %, silica fume %, water content, coarse aggregate %, superplasticizer dosage	[17]
High-strength self-compacting concrete (HSSCC)	Maximize strength and minimize permeability	L18	6 factors: water/cement ratio, total water, fine/total aggregate ratio, fly ash %, air-entraining agent, superplasticizer	[18]
Concrete materials optimization	Determine optimum mix for strength and workability	L9	4 factors: cement %, sand %, coarse aggregate %, water/cement ratio	[19]
Concrete with steel-slag aggregate	Improve strength using steel-slag aggregate	L9	5 factors: natural fine aggregate %, steel-slag fine aggregate %, natural coarse aggregate %, steel-slag coarse aggregate %, water/cement ratio	[20]
Concrete with recycled mixed plastic fine aggregate	Multi-objective optimization with recycled plastics	L9 (3^4)	4 factors: cement content, water/cement ratio, fine aggregate ratio, % recycled plastic	[21]

Application	Objective	Orthogonal array	No. factors & key factors	Ref.
Concrete with mixed recycled aggregates	Optimize mechanical properties using recycled aggregates	L9 + RSM	4 factors: recycled aggregate %, water/cement ratio, superplasticizer dosage, curing time	[22]
Self-compacting alkali-activated concrete	Enhance fracture resistance and reduce brittleness	L9	4 factors: activator ratio, fly ash %, aggregate %, curing time	[23]
SCC with industrial by-products	Optimize mechanical properties using industrial by-products	L9 (Grey-Taguchi)	4 factors: fly ash %, slag %, water/binder ratio, superplasticizer dosage	[24]
Geopolymer concrete (fly ash, GGBS, silica fume)	Optimize geopolymer mix	L9	4 factors: fly ash %, ground-granulated blast-furnace slag %, silica fume %, activator concentration	[25]
Metakaolin-based geopolymer paste	Predict & optimize compressive strength combining Taguchi design with bagging ML	L9 + CCD hybrid	3 factors: NaOH molarity, Na_2SiO_3/NaOH ratio, solid/liquid ratio	[26]
Waste-slurry-based geopolymer concrete	Optimize durability and microstructure of WSGPC	L16 (4^3)	3 factors: slag powder %, alkali activator dosage, activator modulus	[27]
Fiber-reinforced synthetic aggregate concrete	Improve mechanical properties with shaped synthetic aggregates	L9 (Grey-Taguchi)	4 factors: synthetic aggregate %, fiber %, water/binder ratio, curing method	[28]
Fiber-reinforced railway sleepers	Optimize fiber-reinforced concrete mix	L9	4 factors: fiber type, fiber volume fraction, water/cement ratio, superplasticizer dosage	[29]
RC beams under corrosion	Optimize design of RC beams exposed to corrosion	L27	6 factors: concrete cover, water/cement ratio, bar diameter, corrosion rate, binder type, curing method	[30]

Table 1 confirms that the most widespread applications of the Taguchi method in civil engineering concern concrete mix design and sustainable materials, where it has been employed to optimize both conventional and innovative concretes.

Across these studies, key parameters such as the water/cement ratio, binder composition (fly ash, silica fume, slag, metakaolin), and superplasticizer dosage consistently dominate performance outcomes, whether the goal is to maximize strength, improve durability, or enhance workability ([16-19,23-25]).

The method has been extended beyond high-strength and self-compacting concretes to recycled and waste-based mixtures—including plastics, mixed recycled aggregates, and waste slurry—as well as geopolymer and alkali-activated systems, underscoring its value for sustainability-driven innovations ([20-22,25-27]).

Notably, Taguchi designs have been applied to fiber-reinforced concretes, both with shaped synthetic aggregates and for railway sleepers, where fiber type and volume proved decisive ([28,29]).

Durability-focused work, such as the optimization of reinforced concrete beams exposed to corrosion, demonstrates how the approach captures the combined effects of concrete cover, binder type, and environmental exposure variables with a manageable number of tests ([30]).

Table 2 Previous applications of Taguchi orthogonal arrays in structural elements and durability

Application	Objective	Orthogonal array	No. factors & key factors	Ref.
Ultra-high-performance concrete guardrail	Robust multi-objective design of UHPC guardrail	L9	3 factors: UHPC mix ratio, reinforcement configuration, curing conditions	[31]
High-performance concrete columns	Optimize columns for earthquake-resilient design	L27 + RSM	5 factors: water/binder ratio, silica fume %, fly ash %, curing temperature, superplasticizer dosage	[32]
CFDST members with stainless steel tube	Study transverse-impact resistance of double-skin tubes	L9	3 factors: impact energy, hollowness ratio, axial load level	[33]

Table 2 now highlights a more focused set of Taguchi applications dealing with the structural performance of innovative elements rather than concrete-mix optimization.

The studies cover three representative cases: (1) the multi-objective design of ultra-high-performance concrete (UHPC) guardrails, where mix ratio, reinforcement configuration, and curing conditions were tuned using an L9 array to balance strength and durability ([31]); (2) high-performance concrete columns for earthquake-resistant structures, in which a larger L27 design combined with Response Surface Methodology enabled the exploration of five interacting variables related to binder composition and curing regime ([32]); and (3) concrete-filled double-skin tubular (CFDST) members, where an L9 array isolated the key effects of impact energy, hollowness ratio, and axial load level on transverse-impact resistance ([33]).

Together these studies demonstrate how Taguchi designs can efficiently identify the critical geometric and material parameters that govern structural capacity and impact or seismic performance, while keeping the number of experimental runs manageable even when multiple factors are involved.

Table 3 Previous applications of Taguchi orthogonal arrays in bridge and viaduct optimization

Application	Objective	Orthogonal array	No. factors & key factors	Ref.
Multi-objective bridge & viaduct design	Calibrate MOPSO parameters to reduce cost, CO_2 emissions and extend service life	54 tests (orthogonal 3^5)	5 factors: population size, inertia weight, cognitive coefficient, social coefficient, mutation rate	[34]
I-beam bridge multi-objective optimization	Minimize cost and CO_2 while maximizing service life	Taguchi + Simulated Annealing	4 factors: beam spacing, girder depth, concrete strength, reinforcement ratio	[35]
Prestressed concrete bridge pier	Identify critical factors for pier collapse	L9	4 factors: pier geometry, prestress level, reinforcement ratio, concrete strength	[36]
Cable-stayed bridge tensioning (Descent Local Search)	Calibrate parameters of a heuristic algorithm to optimize tensioning of cable-stayed bridges	L18	5 factors: matrix type, max changes in tensioning order, max changes in tensioning stresses, max distance between tensioned stays, max change of tensioning stress	[15]

Table 3 compiles the key studies where Taguchi orthogonal arrays support bridge and viaduct optimization, covering both structural design and algorithmic calibration. The first two cases illustrate how Taguchi designs can work in tandem with metaheuristic algorithms—multi-objective particle swarm optimization (MOPSO) and simulated annealing—to balance cost, CO_2 emissions, and service life by fine-tuning critical design parameters such as population size, inertia weight, beam spacing, and girder depth ([34,35]). Another study applies an L9 array to evaluate the influence of pier geometry, prestress level, reinforcement ratio, and concrete strength on collapse resistance ([36]). Finally, Taguchi principles were used to calibrate the Descent Local Search algorithm for cable-stayed bridge tensioning, identifying optimal settings for variables like tensioning order and allowable stress changes to achieve efficient cable-force distribution ([15]). Collectively, these works demonstrate that Taguchi orthogonal arrays are not limited to material mix optimization; they also provide a structured, low-run experimental framework for complex structural systems and computational optimization of bridge engineering problems.

Table 4 Previous applications of Taguchi orthogonal arrays in inspection and monitoring with Unmanned Aerial Vehicles (UAV)

Application	Objective	Orthogonal array	No. factors & key factors	Ref.
UAV flight calibration for pothole detection	Optimize UAV flight parameters for pavement surveys	L9	3 factors: flight altitude, speed, image overlap	[37]
UAV flight calibration for heritage façades	Optimize UAV parameters for façade deterioration detection	L9	3 factors: altitude, camera angle, speed	[38]

Table 4 highlights the use of Taguchi orthogonal arrays for inspection and monitoring of civil infrastructure with unmanned aerial vehicles (UAVs). Two representative studies demonstrate how L9 arrays can efficiently determine the best combinations of flight altitude, speed, and camera settings to ensure high-quality image capture while minimizing survey time and cost.

The first focuses on pavement surveys for pothole detection, optimizing altitude, speed, and image overlap to improve detection accuracy ([37]). The second applies a similar approach to the inspection of heritage façades, calibrating altitude, camera angle, and speed to enhance the identification of surface deterioration in historic structures ([38]). Together these works show that Taguchi designs can streamline the experimental calibration of UAV parameters, providing reliable data acquisition strategies for both routine maintenance and heritage conservation with a limited number of test flights.

3 Potential Applications of the Taguchi Method in Prestressed Concrete Structures

Prestressed concrete (PSC) design and construction involve complex interactions among prestress level, tendon configuration, concrete mix, time-dependent losses, and construction tolerances. Environmental factors such as temperature fluctuations and humidity introduce additional uncertainty, making PSC an ideal candidate for robust design methodologies. Yet, despite this clear potential, the application of the Taguchi method to PSC structures remains extremely limited. A review of the available literature reveals only scattered or indirect references and no comprehensive exploration of how Taguchi techniques could address the unique challenges of PSC systems, even as the demand for economical and durable prestressed infrastructure continues to rise. Within the surveyed studies, only one explicit application targets PSC directly: the design optimization of a prestressed concrete bridge pier. This investigation [35] employed an L9 orthogonal array to systematically vary pier geometry, prestress level, reinforcement ratio, and concrete strength, identifying the most influential parameters governing ultimate load capacity and susceptibility to collapse. In this work, the researchers ranked factor significance and determined an optimal configuration that minimizes material use while ensuring structural safety and serviceability. This work illustrates how Taguchi's robust design framework can support PSC bridge engineering in achieving cost-efficient, performance-oriented solutions—a notable contrast to the many Taguchi studies focused on conventional (non-prestressed) concrete.

Despite its limited application in the PSC field reported in the literature, Taguchi's orthogonal arrays can still provide valuable insights at the following stages of a PSC structure's life cycle.

3.1 *Design and Material Dosage*

During the conceptual and mix-design stage, the performance of a PSC system is dictated by the composition and quality of its constituent materials. Taguchi orthogonal arrays make it possible to evaluate, in a limited number of trials, the combined influence of cement content, water–cement ratio, aggregate grading, and supplementary cementitious materials such as fly ash, silica fume, or metakaolin. This is especially valuable when exploring novel concretes: mixes incorporating recycled aggregates, ground glass powders, or industrial by-products to reduce embodied carbon, as well as ultra-lightweight concretes that lower structural weight but introduce new variability in strength and stiffness.

Chemical admixtures further expand the design space. In fact, superplasticizers, shrinkage reducers, and internal-curing agents control workability, setting time, and early-age strength, while their interactions with new aggregates or binders can be complex.

Similarly, the incorporation of fiber reinforcement adds another layer of optimization: steel, polypropylene, basalt, or hybrid fibers, combined at different dosages and aspect ratios, can enhance ductility, impact resistance, and long-term durability. Orthogonal arrays allow researchers to study the simultaneous effects of fiber type, volume fraction, and dispersion quality, together with concrete mix variables and prestress level, to identify robust combinations that ensure strength, stiffness, and serviceability over the structure's life.

3.2 *Production and Prefabrication*

Once the mixture proportions and structural configuration are established, attention shifts to the production stage, where process parameters exert a decisive influence on the final quality of prestressed concrete (PSC) elements.

In precast plants, Taguchi experiments can be used to optimize steam-curing regimes, systematically varying temperature, humidity control, and duration to achieve a balance between rapid strength development and the avoidance of thermal cracking.

Other production factors—such as vibration energy, form-release timing, and curing-membrane application—can also be treated as experimental variables to ensure consistent compaction, dimensional accuracy, and surface finish across elements.

The prestressing operations themselves add another layer of complexity. Key variables include the sequence and rate of tendon tensioning, the timing of detensioning relative to concrete maturity, and the temperature profile during tensioning operations, all of which directly affect the final prestress level and the magnitude of long-term losses.

Moreover, prestressing strategies—such as pre-tensioning versus post-tensioning, bonded versus unbonded tendons, and different tendon profiles or eccentricities—can be systematically evaluated within Taguchi orthogonal arrays.

This makes it possible to quantify how prestressing choices interact with material characteristics to influence mid-span deflection, time-dependent losses, crack propagation, and overall serviceability.

These considerations become especially critical when innovative concretes are employed, such as high-recycled-content mixes, ultra-high-performance concretes (UHPC), or fiber-reinforced matrices.

The sensitivity of these materials to curing conditions, prestressing timing, and temperature variation means that process parameters must be carefully optimized to unlock their full structural potential.

3.3 Construction and Erection

During the transportation and assembly phase, large prestressed concrete (PSC) members are subjected to significant handling stresses that can critically affect their integrity.

Taguchi orthogonal arrays provide a structured way to evaluate lifting-point locations, sling angles, crane sequencing, temporary bracing arrangements, and transport vibration levels, enabling the identification of configurations that minimize peak tensile strains, local stress concentrations, and risk of cracking during handling.

This systematic approach is particularly valuable for long-span girders or slender precast segments, where improper lifting or vibration during transit can compromise service performance before installation.

Once on site, assembly operations introduce additional challenges, especially for post-tensioned systems.

The grouting of ducts must guarantee complete tendon encapsulation, corrosion protection, and adequate bond strength, yet outcomes are highly sensitive to grout composition, injection pressure, and temperature control.

By incorporating these variables into orthogonal arrays—together with ambient weather conditions such as temperature and humidity—engineers can identify robust combinations that shorten erection time, prevent void formation, and ensure reliable tendon performance.

Moreover, factors related to jointing and continuity, such as shear-key geometry, epoxy application, or temporary stressing sequence, can also be optimized using Taguchi designs. This ensures that precast segments achieve proper alignment and transfer forces effectively, reducing the likelihood of differential deflections or early cracking.

3.4 Service and Operation

After commissioning, prestressed concrete (PSC) structures are expected to deliver reliable performance for several decades, all while facing changing environmental exposures, variable traffic loads, and gradual material degradation.

Ensuring long-term serviceability requires an integrated approach to structural health monitoring (SHM), where numerous decisions must be made regarding sensor type, spatial distribution, sampling rate, data-acquisition interval, and protective housing.

Taguchi orthogonal arrays provide a powerful means to evaluate these factors simultaneously, helping to identify the most economical monitoring configuration that still captures essential indicators of performance, including natural vibration modes, tendon relaxation, long-term deflection trends, crack initiation, and chloride ingress in aggressive environments.

Beyond monitoring, maintenance and management strategies also benefit from robust design principles.

Decisions about surface coating intervals, joint resealing schedules, drainage improvements, or even adaptive traffic-load management can be systematically assessed through Taguchi plans, enabling the development of cost-effective programs that maximize durability and minimize life-cycle costs.

Such an approach allows owners to prioritize interventions based on quantitative evidence of which factors most strongly influence service life.

Furthermore, as digital twins and predictive maintenance models are increasingly integrated into PSC asset management, Taguchi frameworks can serve as a bridge between experimental calibration and digital prediction, ensuring that monitoring data and maintenance actions are optimized together.

3.5 Rehabilitation and End-of-Life

Eventually, many prestressed concrete (PSC) structures reach a stage where strengthening, repair, or controlled deconstruction becomes necessary.

At this point, the choice of intervention methods has a profound impact on safety, cost, and sustainability, and Taguchi experiments can play a key role in guiding these decisions.

For repair and strengthening, orthogonal arrays can be used to evaluate alternative surface-preparation techniques—including sandblasting, hydro-jetting, and mechanical scarification—together with the type, composition, and dosage of repair mortars or fiber-reinforced overlays.

This approach allows engineers to identify the combinations that maximize bond strength, adhesion durability, and compatibility with the existing substrate while minimizing repair-induced stresses.

Where partial post-tensioning is adopted to restore lost capacity, Taguchi plans enable a systematic study of tendon type (steel, CFRP, or hybrid), additional prestress levels, and anchorage configurations, ensuring that strengthening schemes provide adequate safety margins without introducing undesirable secondary effects.

In cases where rehabilitation is no longer viable and structures are destined for dismantling or recycling, Taguchi methods can also inform the optimization of cutting techniques (diamond sawing, hydro-demolition, or thermal methods), dismantling sequences, and separation strategies.

Such evaluations not only minimize cost, time, and worker risk, but also enhance the recovery of reusable materials and components, supporting circular-economy goals by reducing waste and environmental impact.

Table 5 summarized of potential applications of the Taguchi method in PSC structures including typical variables (factors), possible levels, and the targeted purpose.

Table 5 Summary of examples of pursued aims and variables (factors) in different life-cycle stages

Life-cycle stage	Examples of pursued aims	Examples of variables (factors)
Design & Material Dosage	Identify material combinations that enhance strength, stiffness, durability, and early-age performance	Cement content, water/cement ratio, aggregate grading, SCM content, fiber properties, prestress level
Production & Prefabrication	Optimize production quality, reduce variability, and prevent defects, such as thermal cracking or incomplete prestress transfer	Curing temperature, curing time, humidity control, vibration energy, prestressing sequence, detensioning time
Construction & Erection	Minimize handling stresses, avoid cracking, improve joint performance and alignment during assembly	Lifting configurations, sling angles, and crane sequence
Service & Operation	Optimize monitoring systems and maintenance strategies for long-term performance and cost efficiency	Sensor layout, sampling rate, monitoring intervals, and maintenance intervals
Rehabilitation & End-of-Life	Identify efficient, durable, and low-risk repair or dismantling strategies	Surface prep technique, repair mortar type, strengthening prestress level, cutting method

4 Cost-Optimization Methodology for Industrial Precast PSC Buildings

The practical implementation of Taguchi's orthogonal arrays was carried out through a cost optimization study of an industrial building designed and produced by Plisan Prefabricados S.L., a precast concrete company located in Consuegra (Ciudad Real, Spain). The company specializes in the manufacture, supply, and assembly of prefabricated reinforced and prestressed concrete elements for industrial warehouses.

4.1 Input Data

To begin the structural calculations, a set of basic input data must be defined to ensure that the optimized building meets the client's requirements. The first group of assumptions refers to the site conditions. The site is located in the city of Toledo, Spain, approximately 70 km from the PLISAN SL concrete factory (Figure 1). This distance was used to estimate the transportation costs associated with delivering materials to the construction site. To determine the design actions on the building, the following loads were considered according to the Spanish structural codes: a live load of 0.6 kN/m², a snow load of 0.5 kN/m², and a wind pressure of 0.42 kN/m².

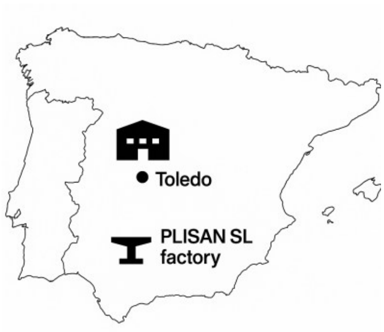

Figure 1 Location of the site and the factory in Spain

The second group of assumptions corresponds to the building dimensions. The span, which is the distance between portal-frame columns and determines the length of the main beams, was fixed to 10 m. The total building length, measured in the plan view, was fixed to 100 m. The clear interior height, defined as the distance from the foundation to the underside of the main beams, was fixed at 8 m. The third group of assumptions relates to the roof type. A gable roof with two slopes and a configuration pitch of 10% was adopted.

4.2 Studied Factors and Levels

Four design factors were selected based on the company's catalogue of standard precast elements and their direct influence on structural configuration and cost:

- Distance between frames (DBF): Levels: 5 m, 6 m, and 7.5 m. This parameter determines the number of structural portals required along the length of the building, directly affecting the total amount of material and the number of elements to be fabricated.
- Beam type (BT): Levels: Reinforced Delta beam (Figure 2a), Prestressed Delta beam for spans higher than 18m, Boomerang beam (Figure 2b). The beam configuration influences both material cost and achievable spans, with prestressing allowing longer spans but requiring more complex production.
- Purlin type (PT): Levels: Tubular section (PT.27 in Figure 2c), T-section purlins T.12, and T.18 (Figure 2d). Purlins define the secondary structure supporting the roof; their cross-section affects load distribution, weight, and transport logistics.
- Column type (CT): Levels: Rectangular 40×40 cm, 40×60 cm, and 50×60 cm. The column size determines vertical capacity and slenderness, influencing both material consumption and handling requirements.

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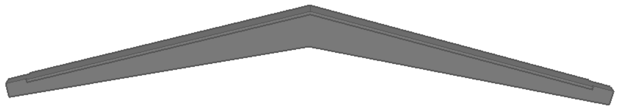
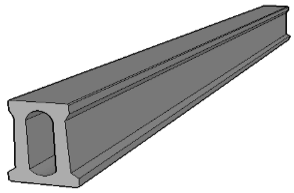
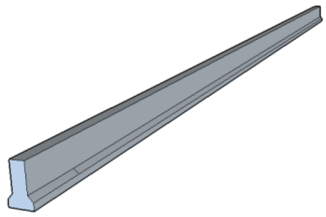
a) Delta beam



b) Boomerang beam



c) Purlin PT27



d) Purling T12 and T18

Figure 2 Elements in the design

Each factor was discretized into three levels, producing 81 possible design combinations in a full factorial scheme.

4.3 Structural Analysis Calculations

The main beams, like the secondary purlins, must resist snow, wind, and live loads. Their load calculations follow the same procedure used for the purlins but also include the beam's own self-weight in addition to the weight of the roof and the purlins themselves. The loads are based on the tributary width of each beam, which depends on the spacing between portal frames. Greater spacing increases the tributary width of both beams and purlins and may require additional purlins so that each beam carries an optimal share of the total load at minimum reinforcement cost. Gable-end and ridge beams were designed in the same way, but each of these edge beams has only half the tributary width of an interior main beam.

After the purlins and beams have been sized, the columns are Each column supports the loads from half of the building span, since every frame rest on two columns.

The overall calculation strategy moves from the top of the structure downward. First, the purlins were designed using the selected frame spacing and the required spacing between purlins to determine the minimum necessary reinforcement. Next, the main beams were selected based on the smallest reinforcement needed for each typology. Finally, the columns were sized, choosing the section and reinforcement that safely carry the combined axial and bending actions. Once the minimum cross-sections and reinforcement for each element have been established, the total production cost for every feasible combination was be calculated. Structural simulations were carried out with the SAP2000 software.

To obtain the production cost of precast concrete elements, the economic cost incurred for manufacturing each piece was considered. This cost includes the resources required for fabrication (concrete and steel), labor costs of factory workers, and the cost associated with the use of molds. As an illustrative example the cost per linear meter of the different reinforcement types of the prestressed delta beam are detailed in Table 6.

Table 6 Cost of prestressed delta beams

Reinforcement type	€/m
T1	80.27
T2	86.32
T3	92.37
T4	98.42
T5	104.47
T6	110.52

The analysis of Table 6 shows that that the cost of the prestressed delta beam varies between 80,27 to 110,52€/m, for reinforcement types T1 and T6, respectively.

4.4 Orthogonal Array Analysis

To investigate the effect of four parameters, each considered at three levels, the Taguchi L9 orthogonal array was employed. The original form of this array is shown in Figure 3a, where the numbers indicate the level assigned to each factor in every experimental run. The adaptation of this generic orthogonal array to the specific case study is shown in Figure 3b. In this customized version, the factors correspond to the main design variables of the structure: DBF (Distance Between Frames), BT (Beam Type), with the options of R. Delta (Reinforced Delta) and P. Delta (Prestressed Delta), PT (Purlin Type), and CT (Column Type).

Using an alternative orthogonal array such as the L18 would introduce additional degrees of freedom that could, in principle, be used to examine selected interaction effects, offering a higher-resolution design when strong interactions are expected. However, our results showed that most main factors were not significant, so increasing the degrees of freedom to analyse their interactions would not provide meaningful insight. Moreover, applying the L18 in this context would require leaving columns unused or forcing the factors into a structure for which the array was not designed, thereby compromising the orthogonality and balance of the experiment. For these reasons the L9 orthogonal array was considered.

Run	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

a) Original L9

Run	DBF (m)	BT	PT	CT
1	5	R. Delta	P.T.27	40x40
2	5	P. Delta	T.12	40x60
3	5	Boomerang	T.18	50x60
4	6,5	R. Delta	T.12	50x60
5	6,5	P. Delta	T.18	40x40
6	6,5	Boomerang	P.T.27	40x60
7	8	R. Delta	T.18	40x60
8	8	P. Delta	P.T.27	50x60
9	8	Boomerang	T.12	40x40

b) L9 adapted to the case study

Figure 3 Orthogonal arrays (DBF: Distance between frames, BT: Beam Type, PT: Purling Type, and CT: Column Type)

The production cost for each of the 9 analyzed simulations is shown in Figure 4.

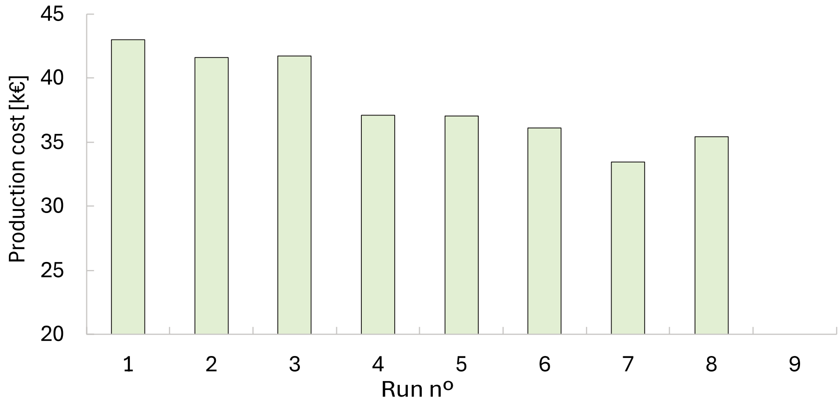


Figure 4 Production cost for each of the analyzed runs

The results indicate a range of values, with the highest cost of €42,978.11 obtained in case 1 and the lowest cost of €33,441.32 in case 7. Notably, no feasible solution was obtained for case 9. This is because the Boomerang beam cannot withstand the loads associated with a frame spacing greater than 6.5 m, as the self-weight generated by the purlins placed on top of the Boomerang beam exceeds the Ultimate Limit State (ULS) capacity of the section.

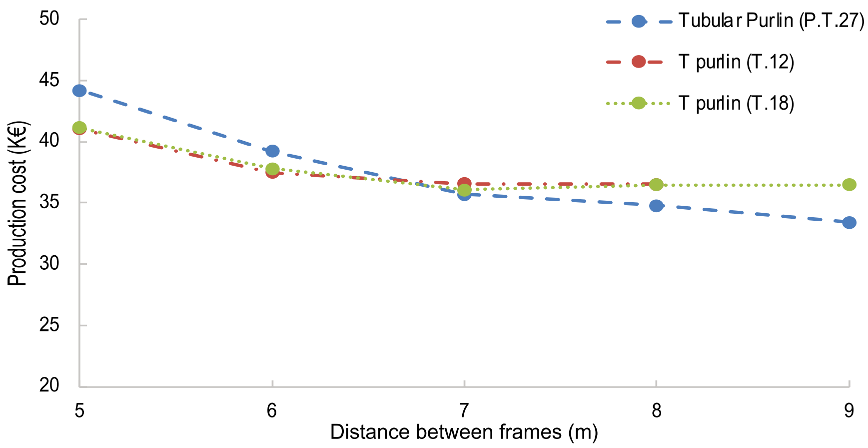
Table 7 was obtained from an ANOVA analysis with the program EasyStatics. This table includes the sum of squares, degrees of freedom (DOF), mean squares, F-values, and p-values for each factor (DBF, BT, PT and CT). The F-value measures the relative contribution of each factor to the variance, while the p-value indicates the probability that the observed differences occurred by chance [15].

Table 7 Summary of ANOVA for each factor

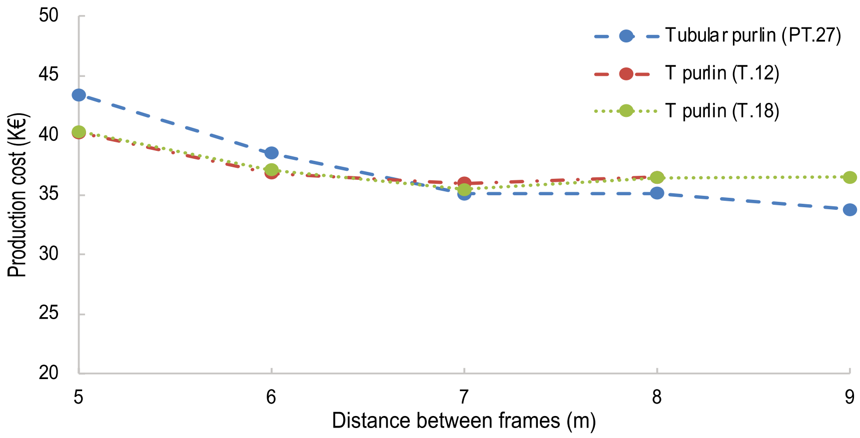
Factor	Sum of squares	DOF	Mean square	F-Value	P-Value
DBF	8.06×10^{7}	2	4.03×10^{7}	55.08	0.0004
BT	3.15×10^{7}	2	1.65×10^{7}	0.05	0.9545
PT	4.49×10^{6}	2	2.24×10^{6}	0.14	0.8719
CT	5.27×10^{7}	2	5.27×10^{6}	0.36	0.7160

The analysis of Table 7 shows that using the conventional threshold of 0.05 for statistical significance, the analysis shows that only the factor DBF (Distance Between Frames) has a significant effect on production cost (p-value= 0.0004). The other parameters (BT (Beam Type), PT (Purlin Type), and PLLT (Pillar Type)) yield p-values above 0.05, which suggests that their influence is not statistically significant within the tested range. The fact that only DBF appears as the only statistically significant parameter in the ANOVA reflects the structural behaviour of the system, in which DBF governs span-induced demands and thus dominates production cost, while the remaining factors produce only secondary variations within realistic design ranges.

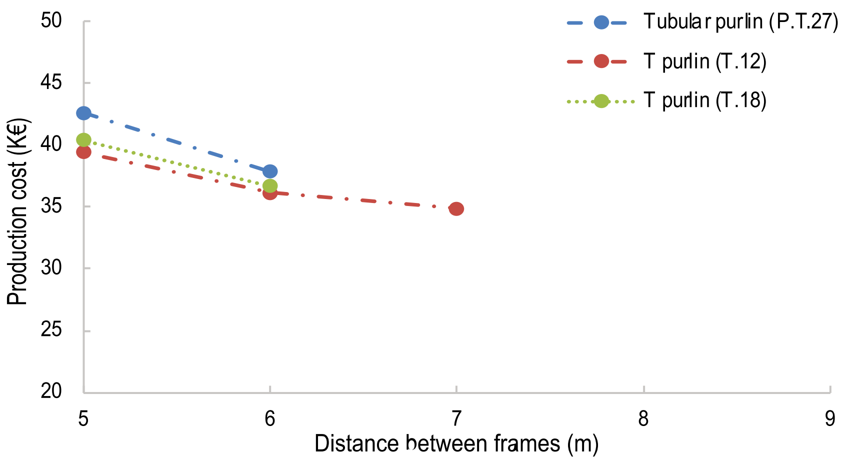
Once it was established that the DBF is the factor most directly influencing the production cost of precast concrete elements, this parameter was discretized into several values in order to evaluate its effect on cost variation. To illustrate these results, the graphs in Figure 5 were generated to illustrate how production cost evolves for different frame spacings (ranging from 5 to 9m). These graphs incorporate the different types of structural purlins and main beams (Reinforced delta in Figure 5a, Prestressed delta in Figure 5b, and Boomerang in Figure 5c), allowing a comparative assessment of their influence on overall cost efficiency.



a) Reinforced delta beam



b) Prestressed delta beam



c) Boomerang beam

Figure 5 Variation of the production cost of the structural components as a function of the distance between frames

The analysis of Figure 5a shows that for a reinforced delta beam the tubular purlin (P.T.27) initially exhibits a higher production cost compared with the other purlin types. However, as the distance between frames increases, the P.T.27 gradually becomes the most cost-effective option in terms of production. In the case of the prestressed delta beam, Figure 5b shows that P.T.27 purlin also represents the least economical solution when the distance between frames is reduced. However, as

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the spacing increases, the tubular purlin becomes the most favorable option in terms of production cost. Finally, the analysis of the boomerang beam showed that solutions beyond a frame spacing of 6.5 m were generally not feasible. This is reflected in Figure 5c, where the curves are interrupted due to the absence of viable solutions. For this configuration, the T.12 purlin emerges as the most economical combination in terms of production cost of the elements. The optimal cost of 33.405,44€ is obtained for the configuration of reinforced delta beams with 9m span and P.T 27 purlins. The decreasing cost trend shown in Figure 5 should not be interpreted as a reduction of safety, as only configurations that satisfy all ultimate and serviceability limit states are included in the curves, while any unsafe or non-compliant designs are automatically excluded from the analysis. For example, the analysis of Figure 5c shows that for large frame spacings of the boomerang beams, several beam–purlin configurations become structurally unfeasible, as the required stiffness and capacity exceed the limits of the available precast elements; consequently, these cases do not yield a valid solution in the optimization process and no solution is presented.

5 Conclusions

This paper demonstrates that Taguchi's design-of-experiments offers a practical and robust framework for managing the multi-factor complexity of prestressed concrete (PSC) throughout its life cycle. A structured literature review shows that, although Taguchi methods are well established in concrete mix design, structural elements, bridge optimization, and UAV-based inspection, their application to PSC remains scarce and fragmented. Building on this gap, the paper reviews and highlights potential applications of the Taguchi methodology across all key stages of a PSC structure's life cycle (design and material dosage, production and prefabrication, construction and erection, service and operation, and rehabilitation or end-of-life) showing where orthogonal arrays, signal-to-noise analysis, and ANOVA can provide clear benefits.

To illustrate these concepts, an industrial case study of a precast PSC building is presented in which four design factors (Distance Between Frames, Beam Type, Purlin Type, and Pillar Section) were analyzed using an L9 orthogonal array to minimize production cost. Analysis of variance revealed that the Distance Between Frames was the dominant cost driver, while the other factors had negligible influence, and a quadratic regression identified an optimal frame spacing that reduced production and transport costs without compromising structural requirements.

By combining an extensive review of potential life-cycle applications with a concrete example of cost-oriented design optimization, this work evidences the significant advantages of Taguchi methods (reduced experimental effort, clear factor ranking, and robust solutions) and illustrates their practical use for PSC structures. The findings aim to encourage researchers and practitioners to integrate Taguchi methodology into their own investigations and decision-making across the entire life cycle of PSC structures, from initial design to end-of-life strategies, to achieve more economical, durable, and reliable outcomes.

The Taguchi method can be properly applied to PSC structures when the relevant design parameters can be meaningfully discretized into a limited number of levels and the system response is dominated by the main effects of these parameters, allowing orthogonal arrays to capture the essential behaviour efficiently. However, its applicability becomes more limited when key variables vary continuously rather than discretely. In such cases, the variable must be approximated by a small number of representative levels to fit the Taguchi framework. Limitations also arise when the structural response is governed by strong or highly nonlinear interactions that a sparse design cannot capture. In these situations, a larger orthogonal array or complementary optimization methods may be required to provide enough degrees of freedom to analyses interaction effects reliably.

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Data availability statement: The data that support the findings of this study are available from the corresponding author, Xia, upon reasonable request.

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AUTHOR BIOGRAPHIES

	**Jose Antonio Lozano Galant** D.Eng, Professor. Working at Civil Engineering, University of Castilla-La Mancha. Research Direction: Construction and Maintenance of Concrete Bridges. Email: joseantonio.lozano@uclm.es		**Carlos Gisbert** D.Eng, Assistant Professor. Working at Civil Engineering, Polytechnical University of Valencia. Research Direction: Design of Concrete Bridges. Email: cargisdo@mes.upv.es
	**Ye Xia** D.Eng, P.E., Associate Professor. Working at Civil Engineering, Tongji University. Research Direction: Bridge engineering, Structural Health Monitoring. Email: yxia@tongji.edu.cn		**Fidel Lozano Galant** D.Arq, Assistant Professor. Working at Building Engineering, University of Castilla-La Mancha. Research Direction: Maintenance of Concrete Bridges and Digital Twins. Email: fidel.lozanogalant@uclm.es
	**Alejandro Mungaray** Eng, Studying at Civil Engineering, University of Castilla-La Mancha. Research Direction: Sustainable Prestressed Concrete, Artificial Intelligence. Email: Alejandro.mungaray@alu.uclm.es		

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