

PROJECT MANAGEMENT BASICS FOR 3D CONCRETE PRINTING: TIME CALCULATION STANDARDS FOR DESIGN AND TECHNOLOGICAL PREPARATION AND QUALITY ASSURANCE

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Abstract. This research establishes the first comprehensive project management framework for 3DCP through quantitative standards for design preparation, technological setup, and quality management. Based on systematic analysis of construction projects completed during 2023-2025 by "Geopolimer" LTD (Kharkiv, Ukraine), we developed mathematical models for time estimation incorporating perimeter length, geometric complexity, and feature count parameters. Regression analysis of project data enabled formulation of predictive equations: design preparation time accounts for base setup, perimeter-dependent modeling, and complexity coefficients (complex curved surfaces with architectural details). Technological preparation time integrates G-code generation, trajectory verification per meter, and build step validation. A systematic complexity classification system evaluates four geometric factors: curved surfaces percentage, architectural detail count, protruding elements, and internal cavity complexity, enabling quantitative risk assessment and resource allocation decisions. The framework incorporates a three-level quality management system with standardized defect classification (aesthetic, attention-required, critical) defining acceptance criteria for crack dimensions, surface porosity, and structural integrity. Trajectory verification methodology enables proactive defect identification, detecting 85-90% of potential issues before production begins. Economic analysis demonstrates 8-12% rework cost avoidance, 15-20% preparation time savings, and 5-10% schedule compression, with return on investment achieved within 0.5-1.5 months. Case study validation on a 174 m² residential structure demonstrates framework effectiveness: calculated preparation time of 45.1 hours versus actual 47.2 hours. The framework facilitates 3DCP transition from experimental technology to predictable industrial process, enabling evidence-based project planning, systematic risk management, and competitive market positioning. Future research directions include expansion to additional printer types, integration with Building Information Modeling workflows, real-time computer vision quality monitoring, and long-term performance tracking for continuous standard refinement.

Keywords: concrete 3D printing; project management; time standards; complexity classification; quality assurance; defect detection.

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1. Introduction

The construction industry faces unprecedented challenges, including labor shortages, rising material costs, and increasing demands for sustainable building practices [1, 2]. Construction 3D printing (*3DCP*) emerges as a transformative technology offering potential solutions through automation, material optimization, and design flexibility. However, the transition from technological capability to industrial implementation requires robust project management frameworks that address planning, resource allocation, quality control, and risk management [3].

Critical management gaps in current *3DCP* practice include.

Absence of standardized time norms – project managers lack reliable estimates for design preparation and technological setup, hindering accurate scheduling and cost forecasting.

Insufficient resource planning tools – without systematic complexity assessment methods, labor and equipment allocation remain largely empirical, leading to inefficiencies and budget overruns.

Limited quality control protocols – the lack of standardized defect classification and verification procedures prevents systematic quality assurance and creates accountability challenges.

Process uncertainties in trajectory planning, material behavior, and geometric accuracy require structured risk management approaches.

This research establishes comprehensive technical, management tools, and software for *3DCP* implementation.

Purpose of the article – develop quantitative standards for design and technological preparation, enabling evidence-based project planning and resource optimization.

2. Review of the literature

Technology adoption frameworks in construction have been extensively studied [4], establishing that successful implementation requires alignment of technical capability, organizational readiness, and management systems. Research on Building Information Modeling (BIM) adoption provides relevant insights: systematic standards development accelerated industry acceptance by providing predictable workflows and cost structures [5].

Critical success factors identified in construction technology literature include: standardized processes (enabling training and quality control), quantifiable performance metrics (supporting decision-making), and risk mitigation protocols

(reducing adoption barriers) [6]. These factors directly inform the development approach for *3DCP* management frameworks.

Work measurement methodologies in manufacturing provide foundational concepts applicable to *3DCP*. Time and motion studies in additive manufacturing [7] demonstrate that preparation time correlates with geometric complexity through quantifiable parameters. However, construction-scale applications introduce unique factors: larger dimensions, material properties, and environmental influences.

Complexity assessment approaches in construction project management typically employ parametric methods [8]. Research on prefabricated construction identifies similar challenges: translating design intent into manufacturable elements, managing geometric variations, and ensuring assembly compatibility [9]. The proposed framework adapts these methodologies to *3DCP* specifics.

Quality control frameworks for *3DCP* remain underdeveloped compared to traditional construction [10]. Previous research [own publication reference] established relationships between process parameters (layer thickness) and quality outcomes (geometric accuracy, surface defects). However, systematic management approaches integrating defect prevention, real-time monitoring, and corrective action protocols are absent from current literature.

Computer vision applications show promise for automated quality assessment [11], but require standardized defect classification schemes and verification protocols to enable practical implementation. The integration of AI-assisted tools for trajectory verification represents an emerging research direction with significant management implications.

Process uncertainty in *3DCP* stems from material rheology variations, environmental factors, and equipment performance fluctuations [12]. Risk management literature emphasizes proactive verification over reactive correction [13]. The proposed trajectory verification methodology addresses this principle by identifying potential issues before production begins.

Economic optimization studies in construction technology adoption [14] demonstrate that systematic planning reduces total project costs through: waste minimization (material optimization), schedule compression (efficient resource utilization), and quality improvement (reduced rework). These benefits justify investment in standardization frameworks.

3. Standards development framework

3.1 Data collection and analysis

The research analyzed completed projects spanning 2023-2025 ("Geopolymer" LTD, Kharkiv), including (data parameters collected):

- project specifications – perimeter length (L_c), area, height, geometric features;
- time records – design preparation (T_{dp}), technological preparation (T_{tp}), total project duration (T_p);
- complexity factors – curved surfaces, architectural details, protruding elements, internal cavities;
- quality metrics – defect occurrence, rework requirements.

Regression analysis identified significant correlations ($R^2 > 0.85$) between geometric parameters and preparation time. Expert validation sessions (3 technology specialists) refined coefficient values and validated practical applicability.

3.2 Design preparation (DP) standards development

Design preparation (T_{dp}) encompasses engineering work adapting architectural documentation to 3DCP technological capabilities.

Process stages:

- architectural documentation analysis;
- geometry verification for printability;
- design adaptation to printer limitations;
- working 3D model creation;
- CAM software preparation for G-code generation.

Time estimation model:

$$T_{dp} = T_0 \times K_{c0} + t_N \times L_c \times K_c,$$

where: T_0 – base constant (4.0 hours), initial setup, software configuration, project initialization; t_N – time per meter perimeter (20 minutes/m) – model development rate; L_c – total wall perimeter includes external, internal, partition walls, m; K_{c0} – base complexity coefficient (overall project complexity); K_c – detailed complexity coefficient (geometric feature adjustments).

This model enables project managers to:

- generate time estimates during proposal development;
- allocate engineering resources based on quantitative requirements;
- establish project milestones with defined deliverables;
- calculate labor costs for accurate pricing.

Example calculation. Residential building $L_c = 85$ m, medium complexity, $K_{c0} = 1.0$ (straight walls with connection diaphragms), $K_c = 1.0$ (balanced geometric features).

$$T_{dp} = 4.0 \times 1.0 + (20/60) \times 85 \times 1.0 = 32.3 \text{ hours.}$$

Time units for T_{dp} are expressed in hours throughout the model, with t_n converted from minutes (20 min/m = 0.333 h/m) for computational consistency.

Resource allocation: 2 engineers \times 16 hours or 1 engineer \times 32 hours (schedule dependent).

3.3 Complexity classification system

Geometric complexity assessment provides a systematic basis for coefficient determination. Base complexity coefficient (K_c) by expert assessment based on table 1.

Table 1 – The complexity coefficient

Level	Characteristics	Coefficient	Typical Applications
Low	Small-scale, straight walls, simple geometry	0.7	Standard modules, basic structures
Medium	Straight walls with structural diaphragms	1.0	Residential buildings, warehouses
High	Curved walls, complex connections, decorative elements	1.2–2.0	Architectural features, custom designs

The detailed complexity coefficient K_c is calculated as:

$$K_c = K_{c1} \times K_{c2} \times K_{c3} \times K_{c4},$$

where: K_{c1} – curved surfaces percentage (low (<10%) – 0.9, medium (10–30%) – 1.0, high (>30%) – 2.0); K_{c2} - architectural details count (low (<10 elements) – 0.95, medium (10–50 elements) – 1.0; high (>50 elements) – 1.5, K_{c3} – protruding elements count (low (<5 elements) – 0.8, medium (5–20 elements) – 1.0, high (>20 elements) – 1.3); K_{c4} – internal cavity complexity (low (absent/simple planar) – 0.9, medium (planar surfaces) – 1.0, high (curved surfaces) – 2.0).

This classification of the management decision support enables:

- risk assessment (higher coefficients indicate increased preparation complexity and potential delays);
- resource planning (coefficient magnitude guides team composition);
- cost estimation (systematic pricing based on quantified complexity rather than subjective assessment);
- client communication (transparent explanation of time/cost variations between projects).

3.4 Technological preparation (TP) standards

Technological preparation encompasses *G*-code generation and verification for print execution:

- 3D model import to CAM software;
- Print parameter configuration (extrusion speed, layer thickness, trajectory direction);
- *G*-code generation (extruder movement paths);
- Program verification (correctness, feasibility, constraint validation).

Time estimation model:

$$T_{tp} = T_0 + t_{h_L} \times L_c + t_{h_k} \times n_k,$$

where: T_0 – time for setup and *G*-code generation, $T_0 = 0.5$ hours; t_{h_L} – verification time per meter (1 min/m = 0.0167 h/m); L_c – total wall perimeter, m; t_{h_k} – verification per build step (2 min/step = 0.0333 h/step); n_k – number of build steps (layers/sections).

Example. Building with $L_c = 85$ m, height $H_w = 3.0$ m, layer height $h_l = 15$ mm:

$$n_k = 3000\text{mm} / 15\text{mm} = 200 \text{ steps},$$

$$T_{tp} = 0.5 + (1/60) \times 85 + (2/60) \times 200 = 8.6 \text{ hours}.$$

This enables scheduling of technical specialists, equipment allocation planning, and identification of optimization opportunities through trajectory analysis.

4. Quality management system

The verification process follows a sequential logic: geometric validation – technological feasibility – optimization – quality assurance, with each stage serving as a gate for the subsequent phase.

Trajectory verification framework:

- geometric correctness (trajectory continuity, intersection detection, angle validation);
- technological validation (speed limits, layer heights, material flow rates, overhang angles);
- optimization (idle movement minimization, collision avoidance);
- quality control (dimensional compliance, structural integrity assurance).

Risk mitigation. Verification identifies 85–90% of potential defects before production, reducing material waste and rework costs by estimated 12–18% based on project data analysis.

Defect classification and control (severity) limits establish quality acceptance criteria (levels):

1 – aesthetic only (crack width <0.5mm, depth <2mm, surface pores <3mm diameter, density <5/dm²), acceptable with client approval;

2 – requires attention (crack width 0.5–1.5mm, depth 2–5mm, surface pores 3–8mm diameter, density 5–15/dm²), corrective action recommended;

3 (critical) – immediate intervention (crack width >1.5mm, depth >5mm, surface pores >8mm diameter, density >15/dm²), component rejection or mandatory repair.

KPI tracking – quality metrics monitored per project enable continuous improvement and benchmarking across project types.

5 Economic analysis

AI integration in 3DCP project management. The framework incorporates artificial intelligence tools at critical decision points: machine learning algorithms optimize trajectory generation by analyzing geometric complexity patterns from historical projects (reducing manual planning time by 15–20%), computer vision systems enable real-time defect detection during trajectory verification phase (achieving 85–90% accuracy in identifying potential surface defects, geometric deviations, and structural anomalies before production), and natural language processing assists operators through conversational interfaces for parameter selection and troubleshooting. AI implementation requires minimal technical infrastructure – cloud-based API access or local deployment options - making it accessible for small to medium construction enterprises. The economic analysis below quantifies investment requirements and returns from this AI-enhanced standardization framework.

Investment requirements (cost-benefit AI-framework):

- standards implementation – 40–64 hours (documentation, training),
- AI tool subscription – \$20–40/month;
- process AI-optimization: 24–80 hours initial setup.

Benefits quantification (based on project database) are shows in table 2.

Table 2 – Benefits quantification

Benefit Category	Impact
Time savings (preparation)	15–20% reduction
Material waste reduction	12–18% decrease
Rework elimination	8–12% cost avoidance
Schedule compression	5–10% faster delivery
Total annual benefit	40–60%

These benefits (table 2) compound over multiple projects, with mature implementation achieving upper range values (60% total annual benefit) after 3–6 months of standardized practice.

Data in table 2 show ROI (payback period 0.5–1.5 months for typical implementation).

Key risks and mitigation strategy are presented in table 3.

Table 3 – Key risks and mitigation

Risk	Probability	Impact	Mitigation Strategy
Engineer resistance	Medium	Medium	Comprehensive training, pilot success demonstration
Tool learning curve	High	Low	Structured onboarding, ongoing support
Standard deviation from practice	Low	Medium	Flexible coefficient adjustment, continuous validation
Technology obsolescence	Low	High	Regular review cycles, modular framework design

6. Case study validation

Framework validation through real project application. To verify practical applicability and accuracy of the developed time estimation models and complexity classification system (table 1), we conducted retrospective analysis comparing traditional approach versus standardized framework on a completed residential construction project. The validation methodology involved: reconstructing actual preparation timeline from project documentation to establish baseline, applying standardized formulas with measured parameters (perimeter, complexity coefficients) to calculate predicted time, comparing predicted versus actual values to assess model accuracy, and evaluating qualitative improvements in resource allocation and defect prevention. This approach enables quantification of both temporal precision (variance percentage) and operational benefits (reduced rework, improved planning reliability).

Project profile - residential structure 174 m², $L_c = 92\text{m}$.

Traditional approach (no standards). Preparation time – 52 hours (estimated retrospectively). Standardized approach (framework applied) – calculated time: $T_{kp} = 35.3\text{h}$, $T_{tp} = 9.8\text{h}$, $T = 45.1\text{h}$. Actual time – 47.2h (variance +4.7%, within

acceptable $\pm 5\%$ tolerance for project management standards). This accuracy enables reliable client commitments and resource scheduling.

Predictable scheduling enabled better resource allocation, trajectory verification prevented two major geometric errors (saving an estimated 18 hours of rework), and systematic quality control reduced client revision cycles.

7. Conclusions

This research establishes the first comprehensive project management framework for construction 3D printing, addressing critical gaps in time standardization, resource optimization, and quality assurance.

Key contributions:

- mathematical models for preparation time estimation enable accurate project planning and cost forecasting across diverse construction applications;
- systematic complexity classification provides quantitative basis for risk assessment and resource allocation decisions;
- quality management protocols with defect classification and verification methodology reduce rework costs and enable systematic process improvement;
- AI integration framework demonstrates practical application of emerging technologies in construction workflows while addressing organizational change management.

Standards enable construction companies to transition 3DCP from experimental technology to predictable production process, accelerating market adoption and competitive positioning.

Widespread adoption of these standards could reduce average 3DCP project costs by 15–25% while improving schedule predictability by 30–40%, accelerating market competitiveness against traditional construction methods.

Future research directions:

- expansion to additional printer types and material systems;
- integration with BIM (Autodesk Revit, ArchiCAD) workflows and digital construction platforms;
- development of real-time quality monitoring systems using computer vision;
- long-term performance tracking and standard refinement based on accumulated project data.

Framework designed for immediate implementation by construction companies, requiring minimal investment while delivering measurable operational improvements.

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ОСНОВИ УПРАВЛІННЯ ПРОЄКТОМ ДЛЯ 3Д-ДРУКУ БЕТОНОМ: СТАНДАРТИ РОЗРАХУНКУ ЧАСУ НА

КОНСТРУКТОРСЬКУ ТА ТЕХНОЛОГІЧНУ ПІДГОТОВКУ ТА ЗАБЕЗПЕЧЕННЯ ЯКОСТІ

Анотація. Дане дослідження встановлює першу комплексну систему управління проектами для 3D друку бетоном через кількісні стандарти конструкторської підготовки, технологічного налаштування та управління якістю. На основі систематичного аналізу будівельних проектів, завершених протягом 2023-2025 років ТОВ "Геополімер" (Харків, Україна), розроблено математичні моделі оцінки часу з урахуванням периметра, геометричної складності та кількості елементів. Регресійний аналіз проектних даних дозволив сформулювати прогнозні рівняння: час конструкторської підготовки враховує базове налаштування, моделювання залежно від периметра та коефіцієнти складності. Час технологічної підготовки інтегрує генерацію G-коду, верифікацію трасекторії на метр та перевірку кроків побудови. Систематична класифікація складності оцінює чотири геометричні фактори: відсоток криволінійних поверхонь, кількість архітектурних деталей, виступаючі елементи та складність внутрішніх порожнин, забезпечуючи кількісну оцінку ризиків та прийняття рішень щодо розподілу ресурсів. Система включає трирівневу систему управління якістю зі стандартизованою класифікацією дефектів (естетичні, що потребують уваги, критичні), що визначає критерії прийнятності для розмірів трищин, пористості поверхні та структурної цілісності. Методологія верифікації трасекторії забезпечує проактивне виявлення дефектів, виявляючи 85-90% потенційних проблем до початку виробництва. Економічний аналіз демонструє зменшення відходів матеріалів на 12-18%, уникнення витрат на переробку на 8-12%, економію часу підготовки на 15-20% та скорочення графіку на 5-10%, з окупністю інвестицій за 0,5-1,5 місяця. Валідація на прикладі житлової структури 174 м² демонструє ефективність системи: розрахований час підготовки 45,1 години проти фактичних 47,2 години становить відхилення 4,7% для стандартів управління проектами. Система сприяє переходу 3D друку бетоном від експериментальної технології до передбачуваного промислового процесу, забезпечуючи науково обґрунтоване планування проектів, систематичне управління ризиками та конкурентне позиціонування на ринку. Майбутні напрямки дослідження включають розширення на додаткові типи принтерів, інтеграцію з робочими процесами інформаційного моделювання будівель, моніторинг якості в реальному часі з використанням комп'ютерного зору та довгострокове відстеження продуктивності для постійного вдосконалення стандартів.

Ключові слова: 3D-друк бетоном; управління проектами; нормування часу; класифікація складності; забезпечення якості; виявлення дефектів.