Codifying Tacit Craftsmanship into Standardized Technical Parameters: A Multi-Criteria Case Study on Underglaze Ceramic Decal Transfer Printing in Taiwan

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ABSTRACT

Underglaze decal transfer printing serves as a critical technological nexus bridging artistic expression and high-precision ceramic manufacturing. However, the irreversible nature of high-temperature vitreous firing poses profound quality control challenges, as microscopic deviations in pre-firing stages systematically compound into irreversible surface defects. Despite its industrial ubiquity, the codification of tacit craft knowledge into standardized technical parameters remains remarkably sparse in current literature. Grounded in an in-depth empirical investigation of Shin Tay Yuan—a pioneering ceramic transfer enterprise in Taiwan—this study integrates extensive shop-floor observations with multi-criteria decision-making to construct a comprehensive quality-evaluation architecture. Employing the Analytic Hierarchy Process (AHP) across six core manufacturing echelons (plate making, ink mixing, printing, drying, transfer, and firing), we quantify the relative priority vectors of 13 primary dimensions and 29 operational indicators. All pairwise comparisons demonstrated robust consistency (CR < 0.1). The empirical findings illuminate that screen mesh precision (62.2%), Printed Ink Layer Thickness (76.1%), and ambient humidity (83.3%) exhibit dominant leverage over final product integrity. By formalizing empirical craft heuristics into an actionable multi-tier quality index, this study bridges the divide between heritage craftsmanship and modern standardized process control, offering pivotal implications for digitalized quality management in specialized ceramic production.

Keywords: Analytic hierarchy process (AHP), Ceramic decal decoration, Process quality control, Tacit knowledge codification, Transfer printing technology, Underglaze decoration

1. Introduction

1.1 Research Background and Problem Formulation

In the historical trajectory of ceramic manufacturing, surface decoration technologies have progressively evolved from manual hand-painting to standardized, high-volume industrial transfer printing. Ceramic decal transfer printing is widely utilized across diverse production sectors:

functional brand typography on sanitary wares, precision decorative motifs on daily-use consumer tableware, and complex foundation outlining in studio ceramics. These applications demonstrate vital industrial utility by stabilizing graphic reproducibility and enhancing operational throughput.

Ceramic decal processing is traditionally partitioned into overglaze, inglaze, and underglaze decorating techniques. Among these, underglaze decal transfer printing presents distinct operational and physicochemical challenges. Because underglaze patterns are deposited directly onto porous bisqueware prior to transparent glazing and subjected to irreversible vitrification temperatures between 1150°C and 1280°C, microscopic variances introduced during screen printing, drying, or manual transfer cannot be retouched post-firing. Any variance in ink viscosity, screen tension, or ambient humidity cascades cumulatively through subsequent manufacturing stages, leading to severe chromatic aberration, glaze bubbling, or pattern rupture.

Despite its ubiquity in production, existing academic inquiries have disproportionately focused on physicochemical mechanisms, material characterizations, and thermodynamic firing behaviors. For example, Pinto et al. [1] characterized the chromogenic mechanics and cobalt-blue crystalline phase transformations in blue-and-white porcelains. Savchenko and Shustova [2] explored sublimation thermal transfer mechanics on ceramic and textile substrates with an emphasis on resolution boundaries. Santos et al. [3] modeled microwave-assisted sintering conditions and aesthetic color behavior in overglaze systems. In specialized screen-printing research, Yu [4] detailed aqueous binder formulations and screen-printing mechanics for single-fire decal papers. While these studies offer rigorous material-level insights, they overlook the socio-technical dynamics of the shop floor—specifically, how artisanal operational experience and manual heuristics interact with mechanical equipment parameters across sequential production workflows.

In manufacturing management, converting such tacit, uncodified artisanal judgment into standardized operational parameters [23] is essential for quality assurance and digital process control. This gap is particularly evident in regional industrial clusters such as Yingge, Taiwan, where specialized craft knowledge remains predominantly embodied in experienced practitioners. Systematically modeling these multi-stage parameters into an objective, hierarchy-based evaluation framework is urgently required to mitigate process variability and safeguard industrial knowledge assets.

1.2 Research Objectives

To address this literature and practical shortfall, this study investigates the underglaze decal transfer manufacturing process of Shin Tay Yuan Transfer Printing Co., Ltd.. Combining qualitative process mapping with multi-criteria decision-making (MCDM), this study addresses three primary objectives:

(1) Construct a comprehensive, multi-echelon technical indicator architecture capturing the full operational lifecycle of underglaze ceramic decal transfer printing (plate making, ink mixing, printing, drying, transfer, and firing).

(2) Apply the Analytic Hierarchy Process (AHP) to empirically determine the relative priority vectors of critical technical dimensions and sub-indicators based on expert judgment.

(3) Analyze the systemic interdependencies between mechanical precision, ambient manufacturing conditions, and shop-floor manual craftsmanship, providing actionable benchmarks for industrial quality control.

1.3 Research Scope and Limitations

In the processing workflow of the ceramic industry, ceramic decal transfer technology has long played an important role and is closely associated with ceramic production processes. However, compared with its practical application, related literature and professional research remain relatively limited, and its key process factors have rarely been systematically organized.

This study takes Shin Tay Yuan Transfer Printing Co., Ltd. as the research object, as its over fifty years of experience and development in overglaze, inglaze, and underglaze decal techniques demonstrate its technical completeness and research value in ceramic decoration processes.

However, considering the differences in process characteristics and application contexts among overglaze, inglaze, and underglaze decal techniques, covering all three may result in an overly broad research scope. Therefore, this study narrows its focus to underglaze transfer printing technology and the construction of its production indicator framework to strengthen the research focus. Since underglaze transfer printing is closely related to overglaze decal techniques, the latter is appropriately discussed in the literature review and technical context as background supplementation. Furthermore, this study examines the practical operational experience of decal transfer production craftsmen and summarizes their shared technical characteristics as an important foundation for understanding the development of key technologies in underglaze transfer printing.

2. Literature Review

Based on the research topic, the relevant literature was categorized into four main areas: historical context, craft techniques, art and surface decoration, and transfer printing techniques. These categories served as the framework for literature collection and organization. The sources included the National Digital Library of Theses and Dissertations in Taiwan, relevant books, academic journal databases, and website information. The National Digital Library of Theses and Dissertations in Taiwan was mainly used to collect studies related to the historical and regional development of Taiwan's ceramic industry, with particular attention to the historical context and transfer of techniques between Beitou and Yingge. Relevant books focused on ceramic craft techniques and applications, as well as the regional development of Taiwan's ceramic industry. Academic journal databases were used to examine studies on ceramic art, surface decoration, and the historical development of ceramic decoration techniques, while website information was used to supplement materials concerning transfer printing techniques and related industry development. Through the integration and analysis of literature from these different sources, the historical context, technical background, and theoretical foundation of this study were established.

2.1 Overall Historical Development

2.1.1 Origin and evolution of ceramic decal transfer technology

Recent studies have emphasized that ceramic art integrates craft practice, cultural meaning, and aesthetic expression. According to Ozidede [5], as an important form of material culture and decorative art, the development of ceramics not only reflects the aesthetic ideas of different periods, but is also influenced by social contexts, artistic styles, and the evolution of production techniques. Tanrıverdi [6] further emphasizes that ceramic art generates representational meanings through material, form, and surface. In this sense, the surface of ceramic works is not merely a decorative layer, but also a field in which cultural memory, aesthetic expression, and artistic concepts can be constructed. This perspective provides a basis for understanding ceramic surface decoration as an important aspect of artistic expression and meaning construction.

Building on this understanding, Kalay [7] explains that, in fields such as painting, graphics, and ceramics, printing generally refers to a set of techniques used to reproduce visual elements, such as images, text, or patterns, on various surfaces. As this method of visual reproduction can also be applied to ceramic surfaces, printing technology has become an important foundation for ceramic surface decoration. From this perspective, the development of ceramic decal transfer technology can be understood as part of the broader evolution of ceramic surface decoration, as it improved the efficiency of pattern reproduction and gradually promoted ceramic decoration toward standardization and mass production.

Hu [8] states that copper plate transfer printing was originally developed as a transfer technique for repeatedly reproducing decorative patterns and was later applied to ceramic decoration. In this technique, patterns engraved on a copper plate are first printed onto thin paper or a gelatin sheet and then transferred onto the surface of ceramic ware. The technique was invented by the British engraver Robert Hancock in 1751 and introduced to the Worcester factory in 1756. It was later adopted by John Wall to improve ceramic production efficiency and reduce costs. Furthermore, Hoskins and Huson [9] indicate that under-glaze tissue ceramic transfer printing is a technique that connects copper plate printing with ceramic decoration. The process mainly involves using engraved or etched copper plates to print patterns containing cobalt blue oxides onto thin tissue. This technique can produce delicate and distinctive visual effects. However, because this method required considerable manual skill and was less efficient in production, screen printing was gradually introduced into related processes as a supplementary method from the 1950s onward.

It should be noted that copper plate transfer printing was primarily a craft innovation within the industrialization of European ceramics. When discussing Taiwan's ceramic industry, the formation of its decorative and transfer printing techniques must be understood within the local ceramic development context. In other words, the development of ceramic decal transfer in Taiwan is not suitable to be directly interpreted through the evolutionary model of eighteenth- and nineteenth-century British copper plate transfer printing, and its transformation and application within the local industrial context require further examination. Therefore, this study first explains the historical origins of ceramic transfer printing in the West before returning to the context of Taiwan's ceramic industry to explore the formation and development of transfer printing techniques and their related forms of expression across different periods.

2.1.2 Decal techniques and the industrialized production of ceramics

According to Petrie [10], with the development of ceramic decoration techniques, transfer printing has gradually become one of the important methods for pattern reproduction and surface decoration. This technique allows pre-printed images or patterns to be transferred onto the surface of ceramic wares. Compared with hand painting, it can improve the stability and efficiency of repeated pattern production, and is therefore closely related to the development of industrial ceramic production.

Wang [11] regards decal techniques as an important application of ceramic transfer printing in industrialized production. Compared with hand-painted decoration, these techniques developed from the concepts of printmaking and printing, in which patterns are first printed onto a transfer medium, transferred onto ceramic ware, and then completed through firing to achieve the final decorative effect. Because these techniques can reproduce identical patterns while reducing production time and technical requirements, they gradually became a common decorative method in ceramic mass production. Depending on process needs, they can be applied to either overglaze or underglaze decoration. In the overglaze process, transferable images and text are first printed onto decal paper, film, or other media, then transferred onto the ceramic surface and fired to achieve color development and adhesion. In contrast, the underglaze process uses clay slip as the pattern material; the pattern is first formed on paper and then transferred onto the ceramic body through the moisture interaction between the paper and the body. The evolution of both processes reflects the shift from hand-painted decoration to printing and transfer printing techniques, allowing ceramic patterns to be reproduced more consistently and applied to mass production, as shown in Table 1.

Table 1. Comparative analysis of overglaze and underglaze transfer printing systems

Parameter / Dimension	**Overglaze Decal Transfer**	**Underglaze Decal Transfer**
Process Sequence	Bisque firing → Glaze application → Glaze firing → Decal application → Low-temp firing	Bisque firing → Decal application → Transparent glaze application → High-temp vitrification
Spatial Position of Motif	Atop the vitrified glaze surface	Encapsulated beneath the vitrified transparent glaze layer
Firing Temperature	780°C–850°C	1150°C–1280°C
Surface Topography	Distinct tactile relief; slightly raised	Completely smooth, coplanar with glaze surface
Chromatic Palette	Broad spectrum (low volatilization of heavy metal oxides)	Restricted palette (high thermal decomposition at elevated temperatures)
Primary End Applications	Decorative art porcelain, commemorative collectables	Daily-use food-contact tableware, durable sanitary

	ceramics

Note. Adapted from Wang (2012) and field data compiled by the author.

2.1.3 The historical development of ceramic decoration techniques in the context of taiwan's ceramic industry

According to Chiang [12] , ceramic decoration techniques gradually developed toward greater efficiency and mass production, Taiwan's ceramic industry also began to take shape during the Qing dynasty. In the first year of the Jiaqing reign period (1796), glazed pottery was already being fired in the Nantou area. By the ninth year of the Jiaqing reign period (1804), Yingge had also gradually developed its ceramic industry and became one of Taiwan's important early ceramic production areas. Later, in addition to Nantou and Yingge, Beitou developed into an important source of ceramic raw materials due to its abundant white clay deposits, while Miaoli became known for decorative ceramic arts. Ceramic production sites were also formerly distributed in areas such as Guiren, Wuqi, and Shalu.

Chiu [13] explained that, during the Japanese colonial period, Beitou benefited from Japanese capital investment and official guidance, taking the lead in promoting the modernization of Taiwan's ceramic industry and becoming an important foundation for the development of modern ceramics in Taiwan. Subsequently, as some ceramic artisans from Beitou moved to Yingge, related production experience was also introduced into the area, further encouraging Yingge's technological transformation and industrial development. Chiang [12] further noted that, to this day, Yingge has developed into one of Taiwan's most concentrated ceramic production areas and is widely known as the "Ceramics Town."

Within this local industrial context, ceramic decoration techniques gradually adjusted in response to production conditions, industrial specialization, and market demand. The application of underglaze blue transfer printing can first be examined through specific artifact records. The "Yingge Double-Phoenix-Double-Happiness-Pattern Plate," collected by the Taiwan Bowl & Dish Museum and dated to approximately 1945–1964, serves as a concrete example for discussing the characteristics of ceramic transfer printing techniques in Yingge [14] . This artifact can also be understood within the broader development of decorative techniques for daily-use ceramics. Hsu [15, p. 112] indicated that, From the 1930s to the 1960s, pictorial decorations on Taiwanese bowls and plates already showed the combined use of various techniques, including painting, printing, press molding, and color spraying. Among them, Yingge products were important examples, reflecting the increasing diversification of decorative methods at that time.

Chen [16] stated that, after the 1970s, improvements in fuel sources and kiln equipment led the Yingge ceramic industry into a stage of transformation. Meanwhile, records from the National Museum of Taiwan History [17] on the "Overglaze transfer printed double happiness pattern cup" indicate that overglaze transfer decoration was already applied to products from northern Taiwan kiln systems during the 1970s and 1980s. This phenomenon corresponds with industry observations that, between 1970 and 1995, market demand became increasingly diversified and overglaze transfer printing gradually became more widespread. Accordingly, the evolution of ceramic transfer printing in Taiwan reveals a developmental context distinct from that of the West, while also highlighting the

significance of underglaze transfer printing within this process. Based on this understanding, the present study further examines the process characteristics and quality formation factors of underglaze transfer printing.

2.2 Focusing on Shin Tay Yuan: A Company with a Relatively Large Market Share

2.2.1 The industrial positioning of shin tay yuan transfer printing factory

In ceramic decoration processes, transfer printing is one of the common methods of pattern transfer. In this process, decals serve as media for carrying images and colors; pre-made patterns are first transferred onto the surface of the ceramic body, allowing the pattern to integrate with the ceramic object. This process not only has a decorative function but also reflects the coordination within the ceramic industry among pattern design, material application, and firing.

Yingge's Shin Tay Yuan transfer printing factory can be regarded as a representative case in the development of Taiwan's ceramic transfer printing industry. According to the official website of the New Taipei City Yingge Ceramics Museum [18] states that, since its establishment in 1970, Shin Tay Yuan has played an important role in Yingge's transfer printing industry and gradually developed into one of Taiwan's representative large-scale transfer printing factories, earning the title of "the No. 1 transfer printing factory in Southeast Asia." The company's official website [19] further shows that Shin Tay Yuan provides specialized decal/transfer papers for ceramic ware, glassware, enamelware, and other materials, including low-temperature transfer paper, heat-transfer paper, ceramic portrait printing, and outsourced transfer application and decoration services. This indicates its technical foundation and industrial representativeness in transfer paper production, ceramic decoration, and the related transfer printing supply chain.

2.2.2 The transformation trajectory of shin tay yuan transfer printing factory

The case of Shin Tay Yuan demonstrates the possibility of sustaining traditional craft techniques while pursuing factory transformation. Based on the article "Intervening in Factory Transformation through a Lifestyle-Oriented Design Perspective: The Possibilities of Shin Tay Yuan Transfer Printing Factory in Yingge" from T22 Magazine, this study explains that a factory is not merely a production site. Through design intervention, it can also reconnect local culture, lifestyle aesthetics, and industrial memory, thereby revealing the new value of traditional industries in contemporary transformation [20].

Shin Tay Yuan is an important representative of transfer printing craftsmanship within Yingge's ceramic industry, having accumulated mature technical development capabilities and rich industrial experience over time. With changes in industrial patterns and tourism demand, Shin Tay Yuan has gradually expanded from its role in professional production to include artistic workshops, DIY experiences, customized products, and other services, thereby beginning to establish more direct connections with general consumers. Subsequently, by organizing its accumulated process experience, historical stories, and factory space, Shin Tay Yuan identified its own distinctive characteristics and transformed the value of its craftsmanship into content that is easier for the public to understand and experience, further establishing a clearer brand positioning and approach to external communication

[20].

2.2.3 The design value of shin tay yuan transfer printing factory

The design value of Shin Tay Yuan Transfer Printing Factory is reflected in giving transfer printing craftsmanship that was originally less visible an opportunity to be understood and experienced by the public. Based on the explanation in T22 Magazine's article [20], the transformation of Shin Tay Yuan is not simply focused on adjustments to the spatial appearance. Instead, through the arrangement of displays, circulation routes, and experiences, visitors are able to further understand the craftsmanship value and local stories behind the products. Therefore, the design value of Shin Tay Yuan is reflected not only in the renewal of its spatial image, but also in making traditional craftsmanship visible in a more approachable way.

2.3 Shop-Floor Process Equipment and Quality Control Parameters

Based on field interviews with production supervisors, the underglaze decal process comprises six sequential stages: plate making, ink mixing, printing, drying, transfer, and firing. Table 2 details the dedicated machinery, while Table 3 summarizes the empirical quality criteria deployed across these operational nodes.

Table 2. Core manufacturing stages and corresponding machinery

Process Stage	Dedicated Machinery / Equipment	Operational Function
Plate Making	Imagesetter, Emulsion Coater, UV Exposure Unit	Translates digital vectors into transparent film and photochemically etches open mesh structures
Ink Mixing	Three-Roll Mill	Applies shear force to disperse inorganic pigment agglomerates into printing medium
Printing	Manual Screen Printing Table	Deposits uniform wet ink films through screen apertures onto transfer paper substrates
Drying	Infrared/Convective Conveyor Drying Belt	Thermally drives off volatile solvents to solidify ink layers without warping paper
Transfer	Manual Operation	Releases pigment layers from paper backing and adheres designs onto porous bisqueware
Firing	Digital Multi-Zone Programmable Electric Kiln	Sockets ware into an automated thermal profile (1150°C–1280°C) for glaze vitrification

Note. Compiled by the author based on empirical shop-floor investigations.

Table 3. Empirical Process Quality Control Benchmarks Across Manufacturing Stages

Process Stage	Key Quality Control Criteria	Shop-Floor Failure Modes
Plate Making	Absolute registration between film and screen; zero pinhole defects in cured emulsion	Pinhole ink leakage; edge serration on fine-line patterns
Ink Mixing	Homogeneous paste rheology; absence of micro-particulate grittiness	Screen mesh clogging; uneven pigment dispersion; pinhole craters
Printing	Continuous aperture clearance; periodic sampling every 30–40 sheets	Screen mesh clogging; uneven pigment dispersion; pinhole craters
Drying	Uniform layer curing; absence of substrate curling or thermal shrinkage	Inter-sheet adhesion; substrate distortion causing dimensional registration errors
Transfer	Complete moisture expulsion; planar adhesion without micro-bubbles or fold artifacts	Glaze crawling; post-firing blistering; localized pattern shearing
Firing	Precision temperature profiling (1150°C--1280°C); regulated heating/soaking curves	Chromatic burning; glaze pinholes; incomplete vitrification

Note. Compiled by the author based on master-artisan interviews.

2.4 Summary

This study identified these dimensions through a review of the literature, including screen printing, ceramic materials, glaze chemistry, process capability, quality management, tacit knowledge, craft industrialization, and technology transfer.

3. Research Methodology

3.1 Hierarchical Framework Construction

This study deployed the Analytic Hierarchy Process (AHP), a multi-criteria decision-making framework formulated by Saaty [24, 25], to codify qualitative technical knowledge into quantitative priority vectors. The evaluation architecture consists of four hierarchical levels:

Level 1 (Goal): Construction of a Technical Indicator Framework for Ceramic Decal Underglaze Transfer Printing.

Level 2 (Core Process Stages): The six sequential operational nodes: Plate Making (S_1), Ink Mixing (S_2), Printing (S_3), Drying (S_4), Transfer (S_5), and Firing (S_6).

Level 3 (Evaluation Dimensions): Thirteen operational dimensions nested within the six process nodes (e.g., Design Drawing vs. Screen Mesh Construction within Plate Making).

Level 4 (Technical Indicators): Twenty-nine specific, actionable operational parameters defining shop-floor quality criteria. The conceptual structure is illustrated in Figure 1.

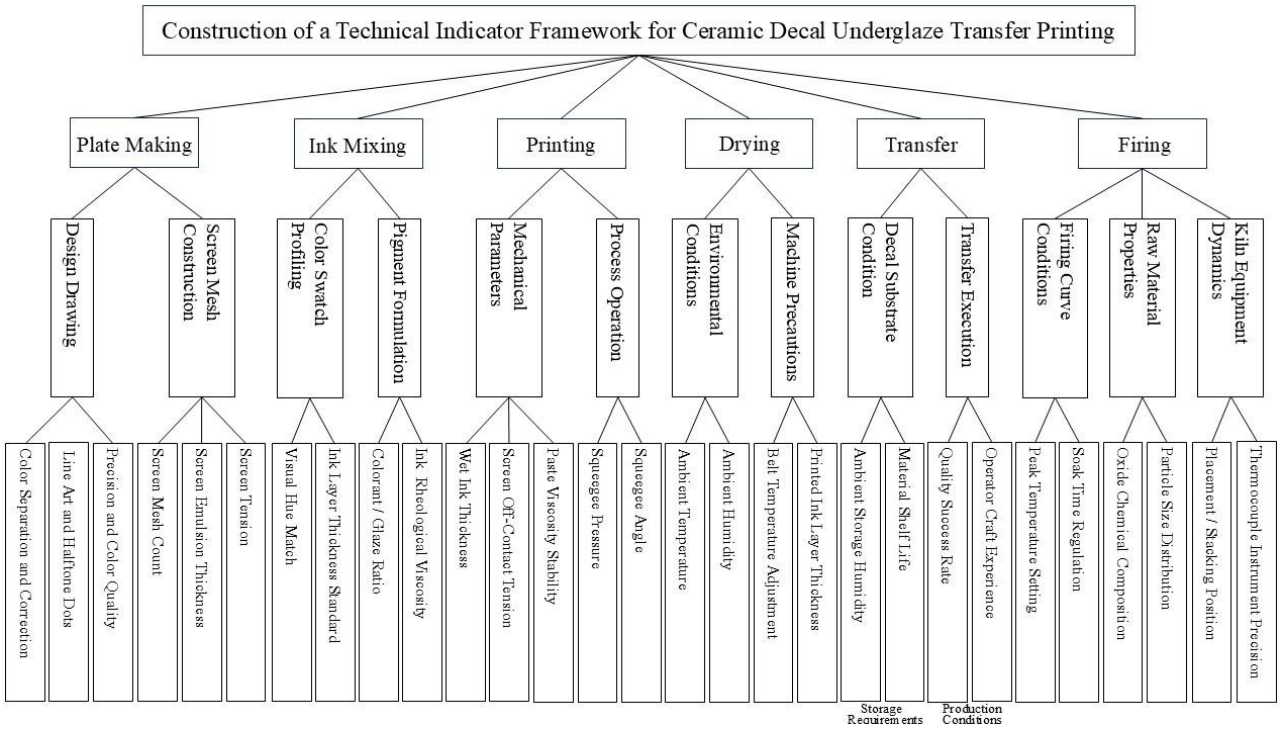


Figure 1. Structural hierarchy of technical indicators for underglaze decal transfer printing

Source: By author

(Note. Synthesized from qualitative field interviews and conference proceedings [Chen, 2026]).

3.2 Expert Panel Composition and Purposive Sampling Strategy

AHP relies on the purposive engagement of highly knowledgeable domain experts rather than statistical sample size (Saaty, 1980, 2008). To capture the full operational interdependencies of underglaze transfer printing, an embedded panel of seven practitioners from Shin Tay Yuan was constructed. All experts operated within an integrated production environment, ensuring that each participant possessed both specialized functional expertise and horizontal awareness of upstream and downstream process constraints. Table 4 outlines the expert profiles.

Table 4. Professional profiles and operational functions of the expert panel (N = 7)

Expert ID	Tenure in Domain	Primary Operational Domain	Formal Organizational Role	Functional Expertise & Justification
E1	40 Years	Printing, Drying, Transfer, Firing	Business Manager	Comprehensive shop-floor master; specializes in line printing parameters and kiln-loading protocols.
E2	40 Years	Ink Mixing & Formulation	Business Manager	Senior colorant specialist; expert in

Expert ID	Tenure in Domain	Primary Operational Domain	Formal Organizational Role	Functional Expertise & Justification
				metal oxide rheology and three-roll dispersion milling.
E3	35 Years	Prepress Design & Color Separation	Senior Designer	Master prepress technician; controls screen dot gain, halftone screening, and color-channel trapping.
E4	30 Years	Prepress Design & Color Separation	Senior Designer	Vector and halftone specialist; oversees photographic image translation for screen exposure
E5	15 Years	Transfer Operations & Defect Auditing	Quality & Cost Auditor (Formal Title: Accounting Staff)	Cross-functional shop-floor practitioner; possesses 15 years of manual decal transfer experience and audits scrap rates.
E6	13 Years	Full-Process Operations & Systems Integration	General Manager	Plant director; manages end-to-end quality standards, equipment calibration, and parameter optimization.
E7	3 Months	Plate Making & Screen Exposure	Operational Staff	Primary frontline operator; provides empirical baseline feedback on standard operating procedure (SOP) compliance and novice execution.

Note. Data gathered from empirical fieldwork.

Methodological Justification of Panel Heterogeneity: In standard industrial AHP applications,

two participant selections warrant explicit defense: Expert E5 (listed as accounting staff) and Expert E7 (3 months of tenure). Expert E5 has participated in hands-on decal application for 15 years while concurrently tracking daily production yield and defect classification, providing an essential intersection of shop-floor practice and quality auditing. Expert E7 was deliberately included to offset the cognitive status-quo bias of senior masters [22]; as a newly trained technician directly executing plate coating and screen washing, E7 reflects the cognitive clarity and standard compliance of current operational documentation. The mathematical consistency of all panel members confirmed the internal validity of the sample.

3.3 AHP Mathematical Modeling and Aggregation

The Analytic Hierarchy Process establishes relative priorities through pairwise comparisons using fundamental judgment scales ranging from 1 (equal importance) to 9 (extreme importance) (Saaty, 1980, 2008). In this study, an adapted 7-point scale with intermediate integers was utilized to facilitate shop-floor evaluation: 1 = Equal, 3 = Moderate, 5 = Strong, 7 = Very Strong, with 2, 4, and 6 serving as intermediate compromises.

Let $A = [a_{ij}]$ represent the positive reciprocal pairwise comparison matrix of size $n \times n$:

$$A = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{pmatrix}$$

where $a_{ij} > 0$, $a_{ji} = \frac{1}{a_{ij}}$, and $a_{ii} = 1$ for all $i, j = 1,2, \ldots, n$.

The local priority vector $w = (w_1, w_2, \ldots, w_n)^T$ was computed using the geometric mean method:

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)^{1/n}}$$

To aggregate judgments across the seven individual experts without violating the reciprocal property of the matrix, the group consensus matrix $A_G = [a_{ij}^G]$ was generated via the geometric mean of individual judgments [21]:

$$a_{ij}^G = \left(\prod_{k=1}^{m} a_{ij}^{(k)}\right)^{1/m}$$

where $a_{ij}^{(k)}$ represents the pairwise judgment of expert k, and $m = 7$ denotes total panel size.

To verify logical consistency, the maximum eigenvalue $\lambda_{\max}$ was calculated:

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(Aw)_i}{w_i}$$

The Consistency Index (CI) and Consistency Ratio (CR) were evaluated:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

where RI represents the empirical Random Index tabulated for matrix size n (Saaty, 1980). A threshold of $CR < 0.10$ signifies acceptable transitivity in expert judgments.

4. Results and Discussion

This study obtained relevant knowledge of ceramic transfer printing technology through a literature review and organization, as well as expert interviews. Subsequently, the evaluation items were further planned and established, and the indicator results were ultimately confirmed through the expert questionnaire. The details are described as follows:

4.1 Literature Analysis

This study mainly referred to the National Digital Library of Theses and Dissertations in Taiwan, books, journal articles, and website information to understand the relevant elements of this field. Since relatively few studies directly focus on underglaze transfer printing, expert consultation was also conducted during the direction-setting stage to further understand the relationship between mechanical equipment and final product quality, and to present the related details.

4.2 Expert Questionnaire Consultation

Since the literature review mainly focused on the historical development context of key technologies in ceramic decal transfer, it was difficult to fully explain the practical application of the technologies and the relationships among the various dimensions. Therefore, this study adopted the expert questionnaire consultation method to consult transfer printing production masters with practical experience in the ceramic industry, in order to understand the relevant knowledge and practical operational experience of ceramic transfer printing technology. In the early stage of the study, based on the preliminary indicator framework, a questionnaire pretest was conducted to integrate the concepts and revise the items. Subsequently, the list of experts was planned, including respondents with diverse practical experience backgrounds, ranging from senior masters to newer practitioners. This was intended to incorporate diverse perspectives and, through the comparison and weighting of expert opinions, make the research results more closely reflect practical applications in the industry.

Therefore, this study further adopted questionnaire surveys and the Analytic Hierarchy Process (AHP) to address aspects that could not be fully covered through the literature analysis, and to provide a more comprehensive interpretation of the technology's development and practical applications.

4.3 Questionnaire Design and Distribution

Based on relevant literature on the construction of technical indicators for ceramic decal transfer (particularly with regard to underglaze transfer printing), this study explored and integrated the related content. Through expert consultation, six core industrial process stages were identified, from which

relevant dimensions and indicators were further developed. In accordance with the pairwise comparison method of the Analytic Hierarchy Process (AHP), the relative importance among the evaluation factors was assessed. Four levels of importance were used: Equal importance (1), Moderate importance (3), Strong importance (5), and Very strong importance (7). In addition, the intermediate values of (2), (4), and (6) were included to make the evaluation more detailed. During the research process, all questionnaires were distributed in physical form. A total of seven questionnaires were collected, all of which were valid, resulting in a response rate of 100%.

4.4 Empirical Priority Vectors and Weight Calculations

All seven completed questionnaires yielded consistency ratios below the critical threshold ($CR < 0.10$), confirming that the expert judgments remained logically consistent across all sub-matrices. Geometric mean aggregation was applied to establish the local priority vectors for each functional dimension and operational indicator. Figure 2 provides a complete schematic of the weight hierarchy, while Table 5 exemplifies the underlying pairwise matrix computation for the Plate Making sub-dimension.

Table 5. Aggregated pairwise comparison matrix and priority weights for plate making dimensions

Dimension	**A. Design Drawing**	**B. Screen Mesh Construction**	**Local Weight (w_i)**
A. Design Drawing	1.000	0.833(5/6)	45.5%
B. Screen Mesh Construction	1.200(6/5)	1.000	54.5%

Note. $\lambda_{\max} = 2.000, CI = 0.000, CR = 0.000 < 0.10$.

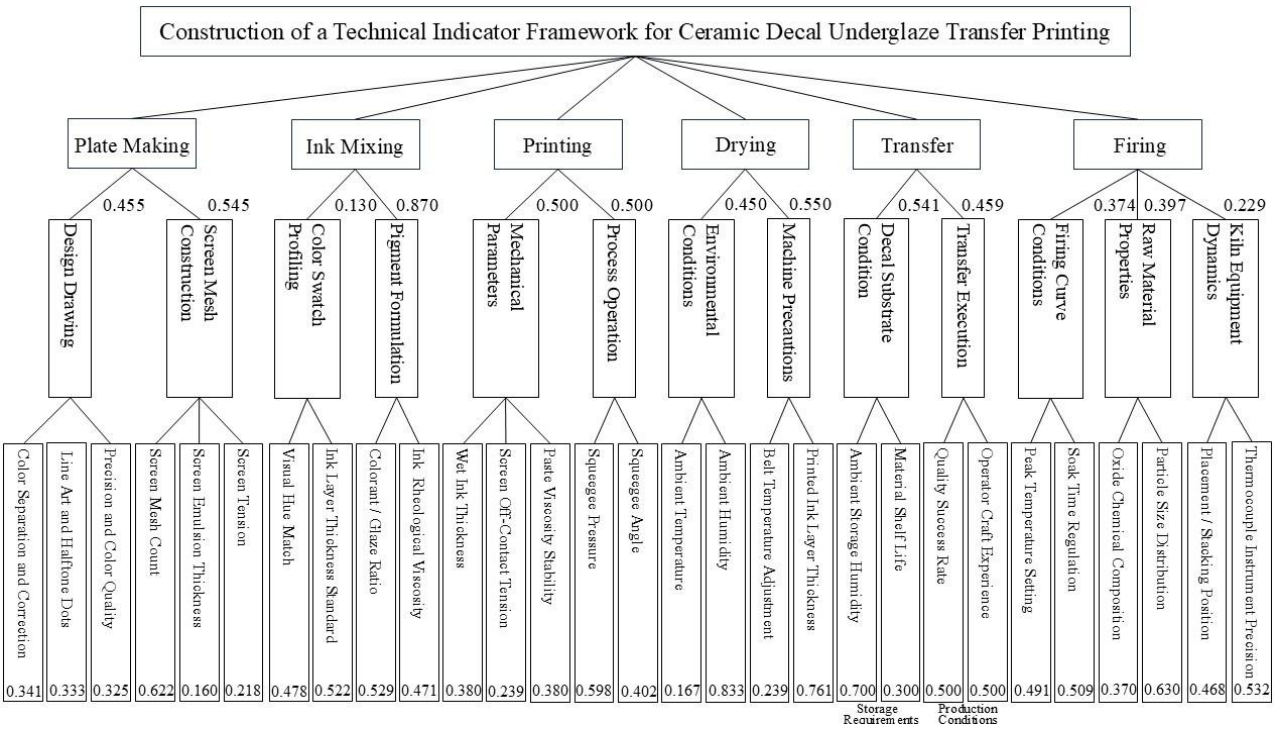


Figure 2. Complete multi-tier weight distribution of technical dimensions and operational indicators (Note. Aggregated priority weights generated via geometric mean evaluation across the expert panel).

Table 6. Consolidated local priority weights across dimensions and technical indicators

Process Stage (S_k)	**Dimension (Level 3)**	**Dimension Weight**	**Technical Indicator (Level 4)**	**Indicator Local Weight**
Plate Making	Design Drawing	45.5%	Color Separation and Correction	34.1%
			Line Art and Halftone Dots	33.3%
			Precision and Color Quality	32.5%
	Screen Mesh Construction	54.5%	Screen Mesh Count	62.2%
			Screen Emulsion Thickness	16.0%
			Screen Tension	21.8%
Ink Mixing	Color Swatch Profiling	13.0%	Visual Hue Match	47.8%
			Ink Layer Thickness Standard	52.2%
	Pigment Formulation	87.0%	Colorant / Glaze Ratio	52.9%

Process Stage (S_k)	Dimension (Level 3)	Dimension Weight	Technical Indicator (Level 4)	Indicator Local Weight
			Ink Rheological Viscosity	47.1%
Printing	Mechanical Parameters	50.0%	Wet Ink Thickness	38.0%
			Screen Off-Contact Tension	23.9%
			Paste Viscosity Stability	38.0%
	Process Operation	50.0%	Squeegee Pressure	59.8%
			Squeegee Angle	40.2%
Drying	Environmental Conditions	45.0%	Ambient Temperature	16.7%
			Ambient Humidity	83.3%
	Machine Precautions	55.0%	Belt Temperature Adjustment	23.9%
			Printed Ink Layer Thickness	76.1%
Transfer	Decal Substrate Condition	54.1%	Ambient Storage Humidity	70.0%
			Material Shelf Life	30.0%
	Transfer Execution	45.9%	Quality Success Rate	50.0%
			Operator Craft Experience	50.0%
Firing	Firing Curve Conditions	37.4%	Peak Temperature Setting	49.1%
			Soak Time Regulation	50.9%
	Raw Material Properties	39.7%	Oxide Chemical Composition	37.0%
			Particle Size Distribution	63.0%
	Kiln Equipment Dynamics	22.9%	Placement / Stacking Position	46.8%
			Thermocouple Instrument Precision	53.2%

Note: Computed from AHP geometric mean group matrices.

5. Conclusions and Implications

5.1 Summary of Key Findings

This study successfully constructs a standardized technical evaluation architecture for underglaze ceramic decal transfer printing by operationalizing shop-floor knowledge through the Analytic Hierarchy Process. By synthesizing evidence from Shin Tay Yuan's operational lineage and multi-criteria panel judgments, several empirical insights emerge:

(1) Ceramic underglaze transfer printing constitutes a tightly coupled, irreversible physical-chemical manufacturing sequence. Prepress and formulation parameters—most notably screen mesh count (62.2%) and colorant / glaze ratio (52.9%)—exert governing control over product viability, disproving the assumption that visual decorative printing is governed primarily by graphic design aesthetics.

(2) Subtropical shop-floor microclimates act as critical quality drivers; ambient humidity levels in drying (83.3%) and storage (70.0%) represent dominant operational failure risks for paper hydro-expansion and ink curing.

(3) Manual craftsmanship and mechanical settings operate in tight interdependence, with manual squeegee pressure (59.8%) and operator transfer dexterity (50.0%) acting as essential stabilizers within semi-mechanized production.

5.2 Theoretical and Methodological Contributions

This research contributes to the operations management and craft industrialization literature in three distinct dimensions:

5.2.1 Codification of tacit craft heuristics

Responding to Nonaka and Takeuchi's [23] knowledge externalization paradigm, this study formalizes tacit, sensory shop-floor craft knowledge into an explicit, structured decision model. It demonstrates how empirical artisanal wisdom can be translated into quantifiable, audit-ready operational parameters.

5.2.2 Interdisciplinary bridging

By integrating graphic communications technology, ceramic materials science, and multi-criteria decision engineering (AHP), this study establishes an integrative analytical framework bridging craft-based regional heritage and rigorous industrial manufacturing systems.

5.2.3 Local priority modeling

Methodologically, by focusing on local dimension weights across six operational echelons, this inquiry provides modular operational benchmarks that production managers can apply directly to specific machine centers without forcing arbitrary cross-stage trade-offs.

5.3 Managerial and Practical Implications

For industrial practitioners and ceramics cluster enterprises, these findings provide immediate operational roadmaps:

5.3.1 Targeted quality auditing

Quality assurance programs must prioritize incoming screen mesh consistency and mechanical

paste dispersion. Implementing digital grain-size analysis on three-roll mill outputs directly mitigates the 63.0% risk vector identified in firing particle defects.

5.3.2 Shop-floor environmental engineering

Ceramic printing facilities operating in humid subtropical climates must transition from ambient curing to closed-loop HVAC systems maintaining strict relative humidity thresholds (<55% RH) across paper conditioning, printing, and drying zones.

5.3.3 Training standardization

The empirical indicator hierarchy provides a foundational curriculum for workforce training, enabling junior operators (such as Expert E7) to systematically master critical mechanical control points (e.g., squeegee pressure and screen tension) rather than relying on decades of unassisted trial-and-error.

5.4 Limitations and Future Research Directions

Several boundary conditions of this study should be recognized:

5.4.1 Single-case enterprise scope

While Shin Tay Yuan offers exceptional historical and technological depth as a regional benchmark, drawing the entire expert panel from a single enterprise introduces potential internal organizational bias. Future research should deploy multi-case comparative designs incorporating overseas ceramic printing clusters (e.g., Arita in Japan, Jingdezhen in China, or Stoke-on-Trent in the United Kingdom) to evaluate cross-cultural parameter generalizability.

5.4.2 Local vs. global weight modeling

This study intentionally modeled local priority vectors within individual process stages to guide station-level engineering. Future studies should administer higher-tier pairwise comparisons across the six primary process stages to construct absolute global priority weights across the entire manufacturing continuum.

5.4.3 Empirical experimental validation

Future research should empirically validate the AHP-derived weight distribution through Taguchi orthogonal experimental designs or response surface methodology (RSM), systematically testing how varying squeegee pressures and drying humidities impact spectrophotometric chromatic stability and bond strength.

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Conflicts of Interest

The author confirms that there are no conflicts of interest.

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