

## Expert Consensus on Post-Processing Techniques for Enhancing the Visual Appearance of FDM 3D-Printed Parts Using the Fuzzy Delphi Method

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### ABSTRACT

*The growing use of Fused Deposition Modeling (FDM) for automotive exterior components is constrained by poor surface quality and the "staircase effect," which fails to meet "Class A" visual standards. To overcome fragmented, trial-and-error manual finishing, this study uses the Fuzzy Delphi Method (FDM) to establish an expert-driven consensus framework. An eleven-member panel evaluated 36 items across six themes using a 7-point Likert scale, which was converted into triangular fuzzy numbers. The findings show that finishing is an interdependent system in which mechanical and chemical sequences govern light reflection, thereby dictating paint smoothness and gloss. Mechanical sandblasting with angular aluminum oxide ( $A = 0.821$ ) serves solely as a preparatory step to level the substrate topography and optimize bonding morphology. This establishes an anchor for chemical finishing, where standardized automotive coating systems, including 2K primers, layer thickness control, and topcoat distribution ( $A \approx 0.882$ ), drive final visual enhancements. These layers eliminate micro-voids, directly optimizing glossiness and aesthetic quality. Ultimately, this transition leads to a standardized engineering pathway, accelerating commercial FDM integration while advancing sustainable manufacturing practices (SDG 9 and SDG 12).*

**Keywords:** Additive manufacturing, Automotive exterior parts, Fused Deposition Modeling (FDM), Fuzzy Delphi Method, Surface Finishing.

### 1. INTRODUCTION

Additive Manufacturing (AM) is a cornerstone of the Industry 4.0 paradigm, driving transformations in personalization, lightweight design, and rapid delivery within the automotive industry [1],[2]. Among AM technologies, Fused Deposition Modeling (FDM) is highly favored for its cost-efficiency, material versatility, and ability to fabricate complex geometries without the need for expensive tooling or molds. The automotive aftermarket, in particular, has seen a surge in FDM adoption for producing custom and replacement exterior parts on demand, enabling manufacturers to reduce inventory requirements and significantly accelerate product development cycles. Despite these advantages, the commercial implementation of FDM for functional automotive exterior parts is significantly hindered by poor surface quality [3],[4]. The inherent layer-by-layer material deposition process creates a discrete, uneven surface profile, commonly known as the "stair-stepping" or "staircase" effect [5],[6]. This defect produces high surface roughness and visible layer lines that consistently fail to meet the stringent "Class A" aesthetic standards required in the automotive industry. In the automotive sector, visual appearance attributes such as surface smoothness, paint quality, and glossiness are critical, as

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they dictate how light interacts with the surface and directly impact consumer perception and product acceptance. In the automotive sector, visual appearance attributes such as surface smoothness, paint quality, and glossiness are critical, as they dictate how light interacts with the surface and directly impact consumer perception and product acceptance.

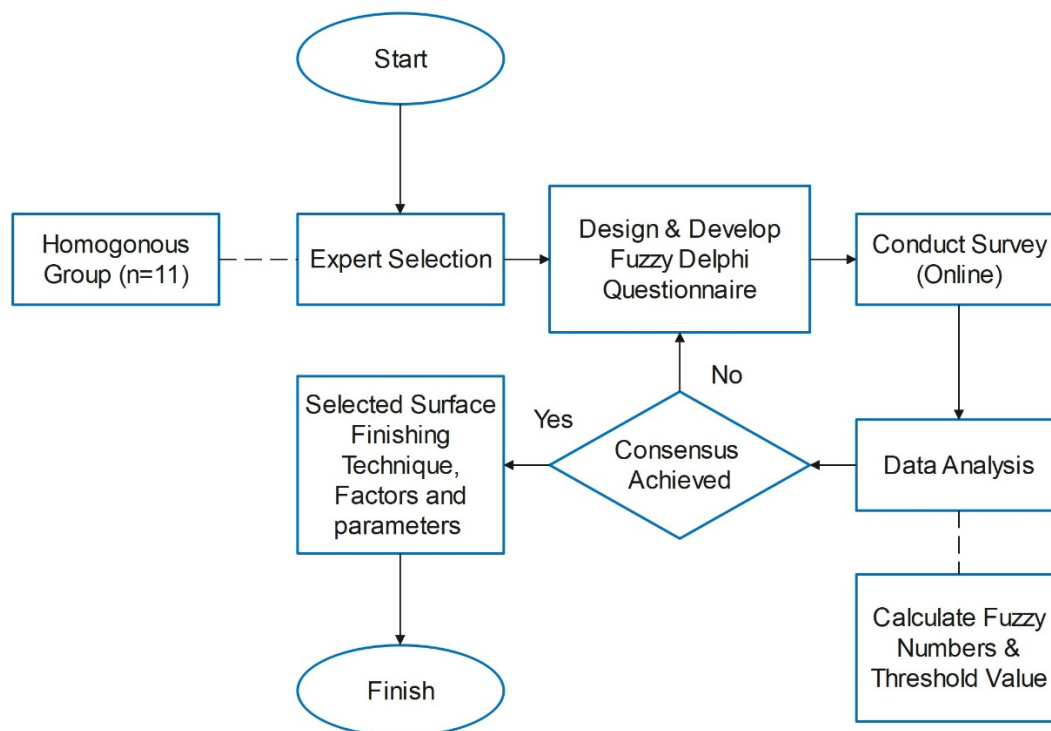
While optimizing pre-processing parameters, such as layer height and print speed, can help mitigate some of these defects, secondary post-processing operations remain essential to eliminate surface irregularities. Post-processing techniques are broadly categorized into mechanical and chemical methods [7],[8]. Mechanical methods, such as sandblasting, utilize abrasive techniques to remove surface imperfections and diminish the staircase effect [3],[9]. Chemical methods, such as spray coating, involve adding subsequent layers (like primers, base coats, and clear coats) to fill residual gaps, protect the substrate, and enhance visual gloss and aesthetics [10],[11],[12],[13],[14]. However, a major challenge in the industry is that current surface finishing practices are highly fragmented and lack systematic integration. Most studies and industrial practices focus on optimizing individual processes in isolation, without considering the cumulative impact of multiple sequential finishing stages. Consequently, surface finishing relies heavily on the trial-and-error manual craftsmanship and “tacit knowledge” of individual operators. This subjectivity leads to a lack of standardization, poor repeatability, and inconsistent visual outcomes across different users. The visual appearance of manufactured components, particularly in the automotive industry, is a critical measure of product quality that relies heavily on three main parameters: color, paint smoothness, and gloss [15],[16],[17]. The correlation between surface finish and visual quality is fundamentally governed by the interaction between surface texture and light reflection behavior.

To overcome the inefficiencies and subjectivity of current finishing practices, a structured, expert-driven approach is required to identify the systematic finishing technique based on the expert consensus and insight. The Delphi technique is a widely accepted group communication process designed to achieve a convergence of opinion on real-world issues by soliciting knowledge from domain experts [18]. The traditional Delphi technique is designed as a group communication process intended to achieve a convergence of opinion on specific issues through multiple iterations [19],[20]. However, it presents significant limitations: the conventional method requires multiple survey rounds (typically 3 or more), making the process costly and time-consuming and prone to low response rates due to respondent fatigue. To account for the natural ambiguity and uncertainty inherent in human judgments, the Fuzzy Delphi Method incorporates fuzzy logic, converting linguistic variables into triangular fuzzy numbers and reducing the need for repetitive and costly survey rounds [21],[22],[23]. Therefore, this paper utilizes the Fuzzy Delphi Method to gain robust expert consensus on the most critical post-processing techniques, factors, and parameters. Integrating FDM into a research methodology significantly strengthens the subsequent experimental procedure. In complex manufacturing systems with a vast array of potential variables, running experiments on all combinations is practically impossible due to material, time, and labor constraints. FDM acts as a critical, analytically filtered bridge between theoretical literature and empirical testing, transforming subjective expert judgment into quantifiable decision-making guidance. The goal is to develop a systematic, multi-stage finishing framework that standardizes the process and enhances the visual appearance of FDM-fabricated Acrylonitrile Butadiene Styrene (ABS) automotive exterior components.

## 2. METHODOLOGY

### 2.1 Research Design

The methodology commenced with the selection of eleven (11) domain experts and the subsequent distribution of a Fuzzy Delphi Method (FDM) questionnaire. Grounded in a comprehensive literature review and preliminary expert consultations, the questionnaire was designed to capture the primary variables governing surface finishing techniques. Using this instrument, a structured survey was administered to the expert panel to elicit their consensus on optimal finishing techniques, critical parameters, and specific elements that determine the aesthetic and structural quality of 3D-printed acrylonitrile butadiene styrene (ABS) exterior components. The gathered qualitative insights were systematically compiled, refined, and validated via FDM analysis, establishing a rigorous, data-driven framework for factor verification. The comprehensive procedural workflow of this research is illustrated in Figure 1.



**Figure 1:** Fuzzy Delphi Flowchart.

The selection of an expert panel constitutes a critical phase in the Fuzzy Delphi Method (FDM), directly governing the reliability and validity of the empirical outcomes. To ensure the acquisition of specialized, high-fidelity insights, this study employed a purposive sampling strategy to select individuals possessing documented credentials, relevant backgrounds, and a high degree of subject-matter expertise. This targeted approach is vital within the FDM framework, where expert opinions are iteratively aggregated and refined to establish robust consensus, thereby enhancing the comprehensiveness and trustworthiness of the findings [22]. Panelists were selected based on three rigorous, predefined inclusion criteria:

- Professional Expertise and Experience:** Experts were required to possess at least 5 years of active professional experience and to be currently engaged in prototyping, model creation, or fabrication using additive manufacturing (3D printing) technologies. This threshold aligns with [24], who posited that a minimum of 5 years' tenure is essential to establish advanced domain skills.

- **Academic Qualifications:** Panellists were required to hold a minimum of a Bachelor's Degree in a relevant engineering or technological discipline, satisfying the requirement for high formal qualifications in expert elicitation processes [25].
- **Diversity of Professional Perspectives:** To capture a well-rounded spectrum of insights, the panel was balanced to include diverse backgrounds spanning academia, industrial manufacturing, and specific technical sub-disciplines.

Methodological literature regarding FDM applications indicates that a minimum sample size of 10 experts is required to ensure adequate compliance and consensus stability [26]. While standard FDM recommendations advocate for a panel size of 10 to 30 experts to achieve a robust consensus, this study established a specialized panel of eleven (11) experts. For the questionnaire, 11 panel experts with at least 5 years of experience in 3D printing and related fields have been selected. Background details on the experts are provided in Table 1 below.

**Table 1:** List of Experts for FDM Consensus.

No	Expert	Company/Institution	Experience (Years)	Position
1	EFDM 1	Pebble3D Sdn Bhd	More than 10 years	Director
2	EFDM 2	AA3D Sdn Bhd	5-10	Director
3	EFDM 3	MIMOS Berhad	More than 10 years	Senior Designer
4	EFDM 4	UTEM	5-10	Designer
5	EFDM 5	Polytechnic Indonesia Surakarta	5-10	Educator
6	EFDM 6	3D Gens Sdn Bhd	More than 10 years	Engineer
7	EFDM 7	3D Forger B3D Group Sdn Bhd	More than 10 years	Designer
8	EFDM 8	UTEM	5-10	Educator
9	EFDM 9	Ejal Designworks	5-10	Designer
10	EFDM 10	AMITEC Sdn Bhd	More than 10 years	Designer
11	EFDM 11	Perodua	5-10	Model Maker

To ensure a balanced and comprehensive evaluation, the selected expert panel comprised a diverse cohort of industry practitioners, product designers, educators, and model-making specialists. These professionals represent a strategic cross-section of both prominent academic institutions and leading industrial organizations, including the Universiti Teknikal Malaysia Melaka (UTeM), Perodua, and various specialized engineering firms. Most of the panelists have 5-10 years of direct domain experience, underscoring the high level of professional credibility and technical expertise that drive this study. This deliberate intersection of diverse operational roles and extensive practical experience guarantees a multi-faceted perspective, crucial for robustly identifying and validating the critical surface-finishing techniques, factors, and parameters under investigation.

## 2.2 Data Collection

The Fuzzy Delphi Method (FDM) questionnaire was systematically developed based on the thematic constructs and code groups identified during the preliminary qualitative analysis phase. To facilitate a robust consensus-seeking process among the expert panel, the instrument was structured to validate and prioritize the critical factors governing surface finishing outcomes.

Data collection utilized a 7-point Likert scale, ranging from 1 (Strongly Disagree) to 7 (Strongly Agree). Compared to traditional 5-point scales, a 7-point configuration was selected to enhance response granularity, minimize central-tendency bias, and optimize psychometric properties, specifically internal consistency and construct validity. By leveraging these methodological advantages, the scale captured highly nuanced expert feedback, thereby reinforcing the precision, reliability, and overall robustness of the consensus-building process. Methodologically, this highly structured approach provides a time-efficient mechanism for deploying standardized,

quantifiable data across a distributed panel. For this study, the questionnaire instrument was structured into two distinct sections as depicted in Table 2:

**Table 2:** Interview question structure.

No	Section	Theme	No of Item
1	Section A	Respondent Demographic	5
2	Section B	Criteria 1: Surface Finish Duration	9
		Criteria 2: Factor Influence the Quality	6
		Criteria 3: Surface Finishing Process	14
		Criteria 4: Mechanical Finishing	11
		Criteria 5: Chemical Finishing	20
		Criteria 6: Surface Quality	10

### 2.3 Data Analysis

The deployment of the Fuzzy Delphi Method (FDM) serves a dual methodological purpose in this study. First, it systematically validates the thematic constructs derived from the qualitative analysis phase, confirming whether they meet the threshold for robust expert consensus. Second, it executes a prioritized ranking of the criteria through defuzzification, thereby transforming subjective linguistic evaluations into quantifiable metrics. This mathematical aggregation facilitates an objective comparison of the variables, providing a rigorous, evidence-based foundation for the final selection of experimental parameters. This study deployed a rigorous data collection and analysis framework utilizing the Fuzzy Delphi Method (FDM), which integrates an explicit 7-point Likert scale with triangular fuzzy numbers (TFNs) and a systematic defuzzification process. The initial phase involved converting the discrete linguistic responses from the 7-point scale into corresponding fuzzy sets. Computational execution and data processing were conducted via Microsoft Excel using the Fuzzy Delphi Template (FDT) developed by Jamil and Noh [27]. The Fuzzy Delphi Method analytical engine comprises two fundamental stages: the construction of TFNs and subsequent defuzzification. To capture the inherent subjectivity and uncertainty of expert opinions, each linguistic variable was mapped onto a TFN, conventionally denoted as an ordered triplet  $(m_1, m_2, m_3)$ . This structural configuration establishes a fuzzy scale that mirrors the Likert scale, systematically translating qualitative human judgment into bounded mathematical intervals. To determine the degree of consensus among the panel, the vertex method was used to calculate the distance between each expert's response and the panel average. The threshold distance ( $d$ ) between two distinct triangular fuzzy numbers, defined as  $m = (m_1, m_2, m_3)$  and  $n = (n_1, n_2, n_3)$ , is mathematically derived using the following formula (Eq. 1):

$$d(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2]} \quad (1)$$

To ensure a highly dependable and scientifically rigorous consensus-building process, two strict validation benchmarks were established based on established FDM precedents:

1. **The Threshold Distance:** The calculated distance ( $d$ ) for each item across all experts must be less than or equal to 0.2 ( $d \leq 0.2$ ). A value within this threshold indicates strong, unanimous expert opinion on that specific variable.
2. **The Consensus Percentage:** A minimum of 75% of the expert panel (75%) must achieve group consensus on the identified items.
3. **The Alpha-Cut Screening:** To satisfy the final screening condition, the defuzzified fuzzy score ( $A$ ) for each item must be greater than or equal to the median ( $\alpha$ -cut) threshold value of 0.5 ( $A \geq 0.5$ ).

By enforcing these dual filtering criteria, the framework effectively filters out highly divergent subjective biases, ensuring that only highly reliable, validated parameters are advanced to the experimental phase. The defuzzification phase was instrumental in determining the definitive ranking and priority hierarchy for each item, variable, and sub-variable within the Fuzzy Delphi Method dataset. By converting the aggregated fuzzy numbers back into crisp, quantifiable real numbers, this process eliminated linguistic ambiguity and established an objective mathematical order of importance. This analytical synthesis, seamlessly integrating qualitative expert insights with a rigorous quantitative framework, underscores the mathematical precision and methodological validity of the Fuzzy Delphi Method in establishing the optimal parameters for this research.

### 3 RESULTS AND DISCUSSION

#### 3.1 Criteria 1: Surface Finish Duration

Criteria 1 evaluates the surface finishing duration, focusing on the temporal efficiency and operational feasibility of the post-processing workflow. This criterion isolates the temporal dimension of manufacturing, assessing how total processing time constrains or optimizes production planning and throughput, rather than evaluating direct geometric or mechanical enhancements to the surface quality.

**Table 3:** Fuzzy Delphi Expert Consensus Decision for Criteria 1: Surface Finish Duration.

No	Item/Element	Condition of Triangular Fuzzy Numbers		Defuzzification Evaluation Process Condition			Fuzzy Score (A)	Expert Consensus Decision
		Threshold (d) value	Expert Consensus Percentage (%)	m1	m2	m3		
C1.6	There are opportunities to improve efficiency in our current processes without compromising quality	0.151	90.91%	0.609	0.809	0.945	0.788	ACCEPTED
C1.7	Implementing new technologies could reduce the overall time required for finishing parts.	0.139	90.91%	0.700	0.873	0.964	0.845	ACCEPTED
C1.8	The painting process, including the use of primers and multiple coats, significantly impacts the overall time required for post-finishing.	0.154	90.91%	0.736	0.891	0.964	0.864	ACCEPTED

Item C1.6 achieved an exceptionally high expert consensus of 90.9% alongside compliant threshold distance values ( $d \leq 0.2$ ). This strong convergence underscores the panel's agreement that manufacturing throughput can be significantly enhanced by refining workflow management rather than enforcing arbitrary completion dates. Furthermore, C1.7 and C1.8 were validated with highly robust defuzzified fuzzy scores of  $A = 0.845$  and  $A = 0.864$ , respectively, comfortably

exceeding the required alpha-cut threshold ( $A \geq 0.5$ ). The acceptance of C1.7 highlights an industry-wide push to adopt innovative, non-traditional finishing techniques to shorten post-processing cycles. Concurrently, the high C1.8 score isolates the coating and painting phases as the primary operational bottlenecks in the additive manufacturing post-treatment pipeline.

### 3.2 Criteria 2: Factors Influencing Surface Quality

Criteria 2 evaluates the fabrication-related parameters that dictate initial surface topography prior to the application of secondary finishing treatments. This criterion directly aligns with the pre-processing domain established in the qualitative code network analysis, capturing the upstream fused deposition modeling (FDM) conditions that fundamentally govern subsequent post-processing requirements and the component's final aesthetic quality. The consolidated empirical data and final expert consensus decisions for this domain are systematically cataloged in Table 2.

**Table 4** Fuzzy Delphi Expert Consensus Decision for Criteria 2: Factors Influencing Surface Quality.

No	Item/Element	Condition of Triangular Fuzzy Numbers		Defuzzification Evaluation Process Condition				Expert Consensus Decision
		Threshold (d) value	Expert Consensus Percentage (%)	m1	m2	m3	Fuzzy Score (A)	
C2.2	The initial setup and settings made by the operator are critical to achieving high-quality prints	0.160	90.9%	0.755	0.900	0.964	0.873	ACCEPTED
C2.3	The configuration and calibration of the 3D printer play a significant role in the quality of the printed part	0.125	100.0%	0.773	0.918	0.982	0.891	ACCEPTED
C2.4	Experienced operators can predict and avoid potential problems before they occur, thereby improving quality control.	0.181	90.9%	0.664	0.836	0.945	0.815	ACCEPTED
C2.6	The quality and consistency of the printing material are crucial for achieving high-quality prints.	0.097	100.0%	0.773	0.927	0.991	0.897	ACCEPTED

The network structure reveals three dominant and interrelated clusters, namely pre-processing parameters, post-processing techniques and processes, and surface quality outcomes. Among these, the post-processing cluster occupies a central operational position within the network, indicating that it serves as the primary control stage that influences the final surface quality of FDM-fabricated automotive exterior parts. Its high groundedness reflects strong expert emphasis, while its high density demonstrates extensive interconnection with both upstream and downstream elements in the finishing workflow. Within this cluster, chemical finishing shows a

balanced combination of strong emphasis and integrative connectivity, suggesting its important role in linking process execution directly to visual appearance outcomes, whereas mechanical finishing exhibits moderate emphasis but lower relational connectivity, indicating that it primarily serves as a preparatory stage rather than a highly integrative one. The pre-processing cluster, although showing moderate frequency, is relatively dense, suggesting it acts as a structural linking element that influences the required finishing intensity and subsequent quality expectations. Meanwhile, the surface quality cluster emerges as the principal evaluation point in the network, shaped by both pre-processing and post-processing clusters, thereby reinforcing its role as the main outcome domain for automotive exterior parts. Overall, the network analysis confirms that surface finishing for FDM-fabricated components should be understood as an interdependent system rather than a sequence of isolated techniques. These relational patterns provided a strong structural basis for abstracting individual codes into higher-level themes, with the abstraction process guided by a dual analytical logic that considered not only frequency-based salience through groundedness but also systemic importance through density and network relationships.

### 3.3 Criteria 3: Surface Finishing Process

Criteria 3 evaluates the operational execution and strategic sequencing of surface finishing workflows for fused deposition modeling (FDM) ABS components. This domain analyzes the critical downstream processing methodologies required to transform raw, as-printed surfaces into high-fidelity, production-grade exterior parts. The consolidated empirical data and final expert consensus decisions for this domain are systematically cataloged in Table 5. The Fuzzy Delphi Method (FDM) analysis for Criteria 3 revealed strong scientific convergence among the panel, successfully validating 11 of the 14 evaluated parameters (78.6%). This high acceptance rate indicates strong expert consensus on the necessity of a highly structured, tightly controlled post-processing sequence to achieve reliable, repeatable surface characteristics. The empirical findings from the FDM analysis confirm that final surface quality is directly determined by rigorous operational sequencing and meticulous process execution. The validated parameters demonstrate that achieving an automotive-grade finish on fused deposition modeling (FDM) ABS substrates requires a shift away from isolated treatments toward a continuous, multi-stage manufacturing workflow.

**Table 5:** Fuzzy Delphi Expert Consensus Decision for Criteria 3: Surface Finishing Process.

No	Item/Element	Condition of Triangular Fuzzy Numbers		Defuzzification Evaluation Process Condition				Expert Consensus Decision
		Threshold (d) value	Expert Consensus Percentage (%)	M1	M2	M3	Fuzzy Score (A)	
C3.1	The current finishing process for FDM ABS 3D-printed parts involves several key stages: initial sanding and preparation, putty application and drying, and primer and paint application.	0.190	90.9%	0.682	0.845	0.945	0.824	ACCEPTED

**Table 6:** Continued.

C3.5	The choice of putty (e.g., red putty with hardener) significantly affects the drying and sanding process	0.125	100.0%	0.700	0.873	0.973	0.848	ACCEPTED
C3.6	Managing the drying time of putty is crucial for maintaining process efficiency.	0.163	90.9%	0.682	0.855	0.955	0.830	ACCEPTED
C3.7	Proper putty application techniques reduce the need for excessive sanding.	0.139	90.9%	0.700	0.873	0.964	0.845	ACCEPTED
C3.8	Using a 2K primer after a plastic primer surfacer is essential for achieving a smooth finish.	0.110	90.9%	0.718	0.891	0.973	0.861	ACCEPTED
C3.9	Proper application of primer ensures good adhesion of the top coat.	0.139	90.9%	0.700	0.873	0.964	0.845	ACCEPTED
C3.10	Manual sanding is necessary to achieve the desired surface smoothness, especially on FDM prints.	0.189	90.9%	0.700	0.864	0.945	0.836	ACCEPTED
C3.11	Achieving surface-smoothness standards, the use of (e.g., 1000-3000 grit) sandpaper is essential for high-quality finishes.	0.179	90.9%	0.718	0.873	0.955	0.848	ACCEPTED
C3.12	The process of applying putty, sanding, and reapplying putty is effective for achieving a smooth surface.	0.181	90.9%	0.664	0.836	0.945	0.815	ACCEPTED

**Table 7:** Continued.

C3.13	Implementing advanced technologies can streamline the finishing process and improve quality.	0.097	100.0%	0.773	0.927	0.991	0.897	ACCEPTED
C3.14	The new approach of finishing processes for FDM ABS 3D printed parts, starting with part removal, sandblasting with Aluminium Oxide, and spray coating, can significantly improve the surface finish and visual appearance of the part compared to traditional methods	0.137	100.0%	0.627	0.818	0.955	0.800	ACCEPTED

The panel strongly supported the need for a standardized, multi-tiered post-processing pipeline. Items C3.1, C3.5, C3.6, C3.7, C3.8, and C3.9 all achieved exceptional consensus thresholds of 90.9% or higher. This strong convergence underscores a strict procedural dependency: high-fidelity exterior part replication requires a precise progression spanning systematic chemical/mechanical surface preparation, controlled body filler (putty) application, regulated drying cycles, interface-building primer applications, and a final protective spray coating. The high consensus highlights that omitting or mismanaging any single phase within this sequence fundamentally destabilizes subsequent layers, leading to surface defects or adhesion failures on the printed polymer. In addition to the macro-level workflow, the experts strongly validated the role of tactile craftsmanship and progressive mechanical abrasion. Items C3.10 (manual sanding for surface smoothness), C3.11 (utilization of fine-grit sandpaper for high-gloss finishes), and C3.12 (iterative putty-and-sanding processes) all received high defuzzified fuzzy scores, comfortably exceeding the  $\alpha$ -cut screening threshold ( $A \leq 0.5$ ).

Rather than advocating rigid automation, the panel's consensus indicates that manual, tactile interventions remain indispensable for addressing the anisotropic step effect inherent to FDM parts. The validation of C3.12 confirms that a cyclical, multi-layered approach, where fine abrasive processing alternates directly with thin filler applications, is the most effective mechanism for eliminating micro-voids, leveling out visible stair-stepping layers, and establishing a uniform, defect-free substrate ready for final coating.

### 3.4 Criteria 4: Mechanical Finishing Process

Criteria 4 evaluates mechanical finishing as an essential preparatory phase within the broader surface post-processing workflow. Rather than serving as a direct determinant of the final aesthetic appearance, this criterion isolates the abrasive mechanical techniques used to condition, clean, and texturize the raw polymer substrate before chemical treatments or secondary coatings are applied. The consolidated empirical data and final expert consensus decisions for this mechanical domain are systematically cataloged in Table 6.

The panel robustly validated the utilization of aluminum oxide as an optimal sandblasting medium (C4.4), yielding a high defuzzified fuzzy score of  $A = 0.821$ . This high ranking is highly significant for additive manufacturing post-processing; unlike rounder media, the sharp, angular morphology of aluminium oxide particles provides a highly efficient cutting action on thermoplastic substrates. This allows rapid leveling of the anisotropic step-textures characteristic of fused deposition modeling (FDM) without causing excessive thermal degradation or surface smearing in ABS. Concurrently, item C4.5 was validated, confirming that the operational success of mechanical conditioning is dependent on precise parametric control. Experts established that surface area roughness,  $Sa$ , material removal rates, and final substrate integrity are direct functions of an interconnected matrix of variables, specifically:

- Pneumatic pressure and exposure duration
- Stand-off distance and impact angle
- Abrasive grit size and media flow rate

The acceptance of these parameters underscores that mechanical conditioning cannot be treated as a generalized, static process. Instead, it must be dynamically calibrated based on the specific geometry and material behaviour of the printed part to prevent structural warping, micro-cracking, or over-abrasion of the delicate polymer features. Ultimately, these outcomes confirm that mechanical finishing serves solely as a critical, preparatory phase rather than a definitive aesthetic treatment. Its primary manufacturing value lies in modifying the initial surface topography and establishing the ideal anchoring morphology required to maximize the bonding efficiency and performance of subsequent chemical finishing treatments.

**Table 8:** Fuzzy Delphi Expert Consensus Decision for Criteria 4: Mechanical Finishing Process.

No	Item/Element	Condition of Triangular Fuzzy Numbers		Defuzzification Evaluation Process Condition				Expert Consensus Decision
		Threshold (d) value	Expert Consensus Percentage (%)	m1	m2	m3	Fuzzy Score (A)	
C4.1	Sandblasting is an effective method for surface preparation and finishing of Fused Deposition Modelling (FDM) 3D printed parts.	0.191	90.9%	0.755	0.891	0.955	0.867	ACCEPTED
C4.3	Glass bead is more effective than other materials (e.g., garnet, aluminium oxide) for sandblasting FDM prints.	0.155	90.9%	0.500	0.691	0.855	0.821	ACCEPTED

**Table 9:** Continued.

C4.4	Aluminium Oxide shows effectiveness to ABS 3D Printed Part surfaces during the sandblasting process.	0.171	90.9%	0.664	0.845	0.955	0.806	ACCEPTED
C4.5	Air Pressure, time, standoff distance, and grit size are process parameters that influence the sandblasting process.	0.190	90.9%	0.645	0.818	0.936	0.800	ACCEPTED
C4.6	Sandblasting allows for better control and precision in targeting specific surfaces of FDM prints.	0.176	81.8%	0.555	0.745	0.900	0.733	ACCEPTED
C4.8	Sandblasting is a time-efficient method for preparing and finishing FDM 3D printed parts.	0.108	81.8%	0.536	0.727	0.900	0.721	ACCEPTED
C4.9	If greater sandblasting pressure or a closer distance is used to modify the sample, the surface will be exfoliated.	0.217	81.8%	0.609	0.782	0.909	0.767	ACCEPTED

### 3.5 Criteria 5: Chemical Finishing

Criteria 5 focuses on chemical finishing as the primary mechanism for enhancing surface appearance, with particular emphasis on gloss, smoothness, and visual uniformity. The resulting expert consensus decisions are summarized in Table 7.

The accepted items strongly emphasize standard automotive coating protocols. Specifically, C5.2 (2K primer utilization), C5.4 (adequate primer drying duration), C5.5 (topcoat quality), C5.8 (paint layer thickness control), and C5.11 (uniform undercoat and topcoat application) achieved both high defuzzified scores ( $A \approx 0.882$ ) and robust expert consensus. These findings verify that regulated primer and paint application are decisive parameters for ensuring consistent surface quality in fused deposition modeling (FDM) acrylonitrile butadiene styrene (ABS) components. Consequently, the results demonstrate that the integrative role of chemical finishing is optimized through conventional automotive coating systems rather than specialized, non-standard methodologies. While chemical finishing serves as the primary stage for final surface enhancement, its efficacy depends entirely on controlled, standardized processes that meet automotive quality and visual acceptance benchmarks.

**Table 10:** Fuzzy Delphi Expert Consensus Decision for Criteria 5: Chemical Finishing.

No	Item/Element	Condition of Triangular Fuzzy Numbers		Defuzzification Evaluation Process Condition				Expert Consensus Decision
		Threshold (d) value	Expert Consensus Percentage (%)	m1	m2	m3	Fuzzy Score (A)	
C5.1	Applying putty to specific areas that need smoothing is an effective method for preparing the surface.	0.181	90.9%	0.664	0.836	0.945	0.815	ACCEPTED
C5.2	Using a 2K primer is essential for achieving a smooth and adhesive surface for subsequent coatings.	0.171	90.9%	0.700	0.864	0.955	0.839	ACCEPTED
C5.4	Allowing adequate drying time for primer layers is crucial for optimal adhesion and finish	0.119	100.00%	0.755	0.909	0.982	0.882	ACCEPTED
C5.5	The quality of the top coat (e.g., gloss, matte) significantly impacts the final appearance of the part	0.119	100.00%	0.755	0.909	0.982	0.882	ACCEPTED
C5.8	Controlling the thickness of each paint layer is important for avoiding drips and achieving a smooth surface.	0.119	100.00%	0.755	0.909	0.982	0.882	ACCEPTED
C5.11	Applying undercoat and topcoat evenly is essential for achieving a uniform finish on the product	0.195	90.91%	0.645	0.827	0.936	0.803	ACCEPTED

### 3.6 Criteria 6: Surface Quality

Criteria 6 designates surface quality as the definitive metric governing the acceptability of fused deposition modeling (FDM) acrylonitrile butadiene styrene (ABS) automotive exterior components. This criterion establishes a critical nexus by converging on material selection, substrate printing parameters, and subsequent chemical finishing processes. The finalized expert consensus decisions are systematically compiled and presented in Table 8.

**Table 11:** Fuzzy Delphi Expert Consensus Decision for Criteria 6: Surface Quality.

No	Item/Element	Condition of Triangular Fuzzy Numbers		Defuzzification Evaluation Process Condition				Expert Consensus Decision
		Threshold (d) value	Expert Consensus Percentage (%)	m1	m2	m3	Fuzzy Score (A)	
C6.1	The selection of material during the 3D printing process significantly affects the ease of post-finishing.	0.190	90.9%	0.682	0.845	0.945	0.824	ACCEPTED
C6.2	Size limitations of FDM printing often require joining parts, which introduces tolerance issues and visible joining lines	0.134	100.0%	0.718	0.882	0.973	0.858	ACCEPTED
C6.3	Ensuring the 3D model is watertight and error-free is crucial to avoiding issues during printing.	0.163	90.9%	0.682	0.855	0.955	0.830	ACCEPTED
C6.4	Continuous monitoring of the printing process is necessary to ensure high-quality output	0.147	100.00%	0.682	0.855	0.964	0.833	ACCEPTED
C6.5	Reducing the layer height during slicing helps to minimize visible layer lines on the printed part	0.155	90.91%	0.664	0.845	0.955	0.821	ACCEPTED
C6.7	The final spray application, after ensuring the surface is defect-free, is crucial for achieving a high-quality finish	0.161	100.00%	0.664	0.836	0.955	0.818	ACCEPTED

**Table 12:** Continued.

C6.8	Establishing quality standards based on customer and researcher feedback ensures the final product meets expectations.	0.163	90.91%	0.682	0.855	0.955	0.830	ACCEPTED
C6.9	Ensuring that there are no surface deformities is critical for the acceptability of the final product	0.125	100.00%	0.700	0.873	0.973	0.848	ACCEPTED

Concurrently, high expert consensus ( $\geq 90.9\%$ ) and elevated defuzzified scores were achieved for C6.1 (material selection), C6.3 (watertight and error-free 3D models), and C6.4 (continuous monitoring of the printing process). These results demonstrate that final surface quality is not merely a function of post-processing finishing techniques but is heavily dictated by upstream parameters in the fused deposition modeling (FDM) workflow. Furthermore, the expert panel validated finishing-specific quality controls; both C6.5 (reducing layer height to minimize staircase effects and visible layer lines) and C6.7 (final spray application exclusively on defect-free substrates) achieved strong consensus, verifying their efficacy in optimizing surface smoothness and visual homogeneity. Crucially, C6.8 (establishing quality benchmarks based on customer and researcher feedback) and C6.9 (ensuring the absolute absence of surface deformities) received unanimous acceptance (100% consensus). This unanimity underscores the critical need for systematic quality evaluation and rigorous defect-mitigation protocols prior to final component deployment. These findings validate surface quality as the final verification benchmark within the finishing workflow. In contrast to the selective acceptance observed in Criteria 4 and 5, Criteria 6 yielded consistently elevated levels of expert consensus across most of its items, establishing its role as a critical, unified standard for part acceptability.

#### 4 CONCLUSION

This study systematically established an expert-driven consensus framework to validate and prioritize the critical post-processing criteria dictating the surface quality of Fused Deposition Modeling (FDM) acrylonitrile butadiene styrene (ABS) automotive exterior components. By transitioning away from fragmented, trial-and-error manual finishing practices governed by operators' tacit knowledge, this research successfully leveraged the Fuzzy Delphi Method (FDM) to mathematically transform qualitative expert insights into a standardized, quantifiable decision-making pathway. The analytical synthesis of the empirical data yields three core conclusions that directly satisfy the primary aim of this study:

- **The Multi-Stage Finishing Pipeline as an Interdependent System:** Network analysis and robust expert validation ( $\geq 90.9\%$  consensus) of items C3.1 through C3.9 confirm that achieving an automotive-grade, "Class A" visual appearance cannot be realized through an isolated treatment. Instead, it requires a continuous, multi-tiered pipeline in which fine-grit tactile mechanical abrasion alternates directly with sequential chemical/coating layers.
- **The Preparatory Role of Mechanical Conditioning:** Mechanical post-processing, specifically sandblasting utilizing sharp, angular aluminum oxide media (C4.4,  $A = 0.821$ ), was validated purely as a preparatory phase rather than a final aesthetic determinant. Its

primary manufacturing utility lies in precision-targeting and altering the initial substrate topography to optimize the interfacial bonding morphology for subsequent treatments.

- **Automotive Coating Integration as the Aesthetic Mainstage:** While *Criteria 6* established final surface quality as the definitive, non-negotiable benchmark for part acceptance, the findings verify that the integrative capacity of chemical finishing is optimized specifically through conventional automotive coating protocols, for example, 2K primers, precise paint layer thickness management, and even topcoat applications yielding ( $A \approx 0.882$ ) over non-standard or specialized methodologies.

Ultimately, this paper demonstrates that final surface quality is a holistic product of both upstream fabrication parameters and highly standardized, downstream multi-stage post-processing workflows. By defining these mathematically validated boundaries, this study bridges the gap between subjective craftsmanship and reproducible manufacturing engineering, facilitating the broader commercial adoption of FDM for functional automotive exterior components while advancing sustainable production standards.

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