

Identifying Critical Post-Processing Criteria for Enhancing Surface Finish of FDM-Printed ABS Automotive Exterior Parts

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ABSTRACT

The increasing adoption of Fused Deposition Modeling (FDM) in automotive manufacturing is constrained by poor surface quality, primarily due to inherent layer-based defects and process-parameter variability. This study aims to identify the critical post-processing criteria that influence the surface finish of FDM-printed ABS automotive exterior parts. A qualitative research approach was employed, involving semi-structured interviews with domain experts, followed by systematic analysis in ATLAS.ti. The data were evaluated through groundedness (Gr) and network density (Gs) to capture both frequency-based importance and structural relationships among factors. A total of 36 codes were generated and subsequently synthesized into six key themes: surface finish duration, factors influencing quality, surface finishing process, mechanical finishing, chemical finishing, and surface quality. The findings indicate that surface finishing is a highly interdependent system, with chemical finishing techniques and process control parameters emerging as dominant contributors to improved surface quality. Surface quality was identified as the central outcome, influenced by both upstream fabrication and downstream finishing processes. This study provides a structured understanding of the critical factors governing finishing effectiveness, offering preliminary insights to support consistent improvement of visual and functional quality in automotive applications, while contributing to sustainable manufacturing practices (SDG 9 and SDG 12).

Keywords: Additive manufacturing, Automotive exterior parts, Fused Deposition Modeling (FDM), Surface finishing, Surface quality.

1. INTRODUCTION

The emergence of Industry 5.0 emphasizes a human-centered manufacturing paradigm that integrates advanced technologies with human creativity and value [1]. Within this context, Additive Manufacturing (AM) has become a key enabler, particularly in supporting customized, flexible, and sustainable production systems [2], [3]. Today, 3D printing is also characterized as Additive Manufacturing (AM) technology [2]. In 3D printing, people can design objects using computer software to create intricate car parts that can be used for various manufacturing purposes. In line with Malaysia's Industry4WRD policy, 3D printing technologies, particularly Fused Deposition Modeling (FDM), have experienced rapid growth in the automotive sector. Traditionally limited to prototyping, FDM is now increasingly adopted for the fabrication of lightweight, geometrically complex, and highly customized functional components. However, despite these advantages, a fundamental limitation of FDM lies in the inherent *staircase effect*, which significantly degrades surface quality [4], [5]. This issue is particularly critical for

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automotive exterior parts, where stringent aesthetic and aerodynamic requirements must be satisfied. In addition to layer-induced surface irregularities, the final surface quality is further influenced by multiple interdependent process parameters during fabrication, including raster width, contour width, raster angle, air gap, support fill density, and processing temperatures [6][7]. The combined variability of these parameters often results in inconsistent surface characteristics, making it difficult to achieve the desired visual appearance directly from the printing process. Consequently, although post-processing is essential to mitigate these defects, the current industrial landscape lacks standardized and systematic guidance, leading to inconsistent finishing outcomes.

Surface finishing, therefore, plays a critical role in bridging this gap, particularly within the automotive industry, where both functional performance and visual quality are paramount. Previous studies have demonstrated that effective surface finishing not only enhances surface layer integrity and operational performance but also improves reliability and extends the service life of automotive components [8]. From a mechanical perspective, finishing processes can reduce surface roughness, improve fatigue strength, and enhance coating adhesion, thereby increasing durability [9], [10]. From an aesthetic standpoint, surface finishing is essential for achieving the desired visual standards, including smoothness, uniform gloss, and a defect-free appearance. Moreover, properly finished surfaces exhibit improved corrosion resistance and coating performance, contributing to long-term durability and product value [11]. For 3D-printed automotive components, achieving a high-quality surface finish is even more critical, as customer acceptance is strongly influenced by visual appearance. In automotive applications, particularly for exterior parts, the concept of a *Class A surface finish* characterized by superior smoothness, uniform reflectivity, and aesthetic excellence is often required to meet market expectations. However, FDM-produced parts inherently fall short of these standards in their as-printed condition, underscoring the need for effective, optimized finishing strategies.

In practice, additive manufacturing is widely applied across various automotive domains, including the production of lightweight engine components, structural optimization of exterior parts such as bumpers and protection systems, and the development of ergonomically optimized interior components [12], [13], [14]. Additionally, FDM is widely used in the automotive aftermarket for repair and customization through reverse engineering. Automakers frequently leverage 3D printing for rapid prototyping, developing customized automotive parts, and streamlining supply chains through the creation of specialized additive manufacturing tooling [15], [16]. Despite these advancements, the transition from functional prototypes to market-ready exterior components remains constrained by limitations in surface quality. Optimizing FDM process parameters is a foundational step in controlling the initial surface topography and structural integrity of printed parts. Parameters such as raster width, contour width, air gap, and support fill density directly influence surface roughness and dimensional stability [17]. Nevertheless, even with optimized printing conditions, the resulting surface quality rarely satisfies the stringent *Class A* requirements of the automotive industry. Therefore, it is essential to strategically integrate printing parameters with appropriate post-processing techniques. For instance, optimized slicing strategies can facilitate more effective mechanical finishing (e.g., sanding or sandblasting) by ensuring sufficient wall thickness, while also improving the effectiveness of chemical finishing methods (e.g., coating or vapor smoothing) through enhanced surface uniformity [18][19].

Failure to align the fabrication and finishing stages often leads to persistent surface defects that negatively affect perceived quality, brand value, and overall customer acceptance. Therefore, it is crucial to establish a clear understanding of the critical factors governing finishing techniques, particularly in relation to their influence on surface roughness and visual appearance. Identifying these key factors provides a necessary preliminary insight into the effectiveness and limitations of different finishing approaches, enabling a more informed evaluation of how surface quality can be consistently improved for automotive exterior applications.

2. METHODOLOGY

2.1 Research Design

This study employed a qualitative research design to capture expert insights into surface finishing techniques and parameters. Semi-structured interviews were conducted with professionals and academics who specialize in additive manufacturing and automotive component finishing. Participants were selected using purposive sampling to ensure a diverse representation of industry practitioners with extensive experience in 3D printing, particularly Fused Deposition Modeling (FDM) processes. The interview protocol was developed based on a review of existing literature and focused on eliciting detailed information about the challenges, best practices, and evaluation criteria for achieving high-quality surface finishes in automotive parts. This qualitative approach provided a comprehensive understanding of current industry standards and highlighted gaps in standardized guidance, thereby informing recommendations for best practices in surface finishing of FDM 3D-printed automotive components. Semi-structured interviews were conducted with three experts selected based on predefined criteria. The participants represented a diverse cross-section of the AM industry, as shown in Table 1.

Table 1: List of Experts for Interview.

No	Expert	Experience (Years)	Position
1	E1	10	Director
2	E2	6	Director
3	E3	27	Senior Designer

As detailed in Table 1, the participants, coded E 1, E 2, and E 3 to maintain confidentiality, represent a robust collective expertise totaling 43 years of experience. The panel includes two Directors with 10 and 6 years of experience, respectively, providing strategic oversight and management perspectives on 3D printing implementation, complemented by a Senior Designer with 27 years of specialized experience in practical design and technical applications. This diverse range of seniority and roles ensures that the data collected on FDM surface finishing parameters is grounded in both long-term industry evolution and modern technical standards, providing a comprehensive foundation for the subsequent thematic analysis. Because optimizing print parameters cannot fully eliminate the stair-step effect, several post-processing techniques are used to refine the surface finish of FDM parts, such as chemical treatment and mechanical finishing.

2.2 Data Collection

The data collection phase was structured to ensure a comprehensive exploration of 3D printing post-processing, specifically focusing on Fused Deposition Modeling (FDM). The process utilized a semi-structured interview protocol designed to balance standardized inquiry with the flexibility for expert elaboration. The interview instrument comprised 23 items categorized into five thematic sections. This modular approach allowed for a systematic transition from general professional insights to highly technical parameters. The organization of the interview questions was carefully structured to address both general and specific areas relevant to the research objectives. This arrangement is detailed in Table 2 below, which outlines the sections and the number of items included in each part of the interview protocol.

Table 2: Interview question structure.

No	Section	No of Item
1	General Questions	8
2	Section A : Surface Finishing Techniques For FDM 3D Printing	6
3	Section B : Important factor in the surface finishing process	4
4	Section C : 3D Printing and surface finishing process parameters to achieve a high-quality surface finish	4
5	Section D : Suggestion and proposal	2

The execution of the interviews followed these specific protocols:

- **Expert Selection:** Three experts were recruited based on pre-defined criteria to ensure specialized insight.
- **Environment & Duration:** Each session lasted approximately 30 minutes and was conducted in a closed discussion room, both in person and online, to maintain a focused, distraction-free environment.
- **Language & Documentation:** Participants were given the flexibility to respond in English or Bahasa Melayu, according to their preference. All discussions were recorded using audiovisual tools to ensure accuracy during transcription and analysis.

Every session was documented using audio-visual recording tools. This dual-mode recording was essential for capturing both verbal nuances and the experts' visual demonstrations. These recordings served as the primary data source for subsequent transcription and thematic analysis, ensuring that the technical complexities of FDM surface finishing were captured with high fidelity.

2.3 Data Analysis

Qualitative data from expert interviews were systematically analyzed using ATLAS.ti software. This ensured a structured and rigorous interpretation of the findings. The analysis began with open coding. During this stage, transcribed data were examined to identify meaningful segments that represented key concepts. Initial codes were generated inductively and then refined through merging and categorization. This process enhanced conceptual clarity and consistency. Two key indicators were used to strengthen the analysis: groundedness (Gr) and density (Gs). Groundedness shows the frequency of code occurrence and reflects the emphasis placed by experts. Density measures how interconnected the codes are and represents their structural significance within the system.

Additionally, code network analysis was conducted to visualize relationships among identified codes. This helped deepen understanding of the interactions between pre-processing parameters, post-processing techniques, and surface quality outcomes. This integrated approach provides a multi-layered interpretation of the data and supports the identification of both dominant and structurally significant factors influencing surface finish.

3 RESULTS AND DISCUSSION

3.1 Code generation

The qualitative coding of expert interview transcripts yielded 36 descriptive codes, capturing recurring technical considerations spanning pre-processing parameters, finishing techniques, process control mechanisms, and surface quality evaluation. Analysis of the three transcripts identified 205 coded segments, reflecting a broad thematic coverage and balanced contributions from each participant. Following the initial descriptive coding, a groundedness (Gr) analysis was performed using ATLAS.ti to evaluate the relative emphasis of each code. In this context,

groundedness refers to the frequency of code application across the dataset and serves as a primary indicator of recurring expert consensus and operational relevance. To complement this frequency-based metric, the density (Gs) of each code was examined to assess its relational connectivity within the conceptual network. While groundedness highlights thematic recurrence, density indicates the degree to which a specific code is structurally interconnected with other concepts. This dual-layer analysis of Gr and Gs ensures a robust evaluation of both thematic emphasis and structural significance within the data. Subsequently, these codes were synthesized into higher-level analytical domains, categorized by their conceptual similarity and functional roles within the FDM fabrication lifecycle.

Table 3: Major code group with groundedness (Gr) and density (Gs).

Code Group	Gr	Gs	Analysis Interpretation
Post-Processing Phase	57	13	Core Operational Domain
FDM 3D Printing	42	4	Fabrication Factor
Surface Quality	24	4	Outcome Evaluation
Chemical Finishing	23	5	Integrative Enhancement
Pre-Processing Phase	21	9	Structural Linkage
Mechanical Finishing	17	2	Operational Preparation
Challenges & Future Consideration	21	7	Strategic Context

Table 3 presents the primary code groups and their respective groundedness (Gr) and density (Gs) values, providing a quantitative basis for evaluating both thematic emphasis and relational significance. The Post-Processing Phase emerged as the dominant analytical domain, characterized by the highest Gr and Gs values, which underscores its central operational role in the FDM workflow. In contrast, the Pre-Processing Phase exhibited moderate frequency but maintained strong relational connectivity; this indicates that while it is discussed less frequently than the finishing stages, it exerts a significant structural influence across multiple downstream considerations. Regarding specific methodologies, Chemical Finishing demonstrated a balanced profile of emphasis and integration, suggesting a well-defined role within the fabrication cycle. Conversely, Mechanical Finishing showed high recurrence but lower density, suggesting a more operationally isolated set of tasks. Finally, Surface Quality served as the evaluative convergence domain, effectively linking upstream parameters with downstream outcomes. This dual-metric approach confirms that the fabrication lifecycle is not merely a linear sequence but a network of interconnected technical decisions, with post-processing as the critical focal point.

Figure 1 illustrates the frequency distribution of individual codes based on their groundedness (Gr) values, as derived from the ATLAS.ti analysis. The data indicates a clear thematic hierarchy, with Finishing Technique – Coating recording the highest frequency (Gr = 19), followed closely by FDM 3D Printing – Material (Gr = 17) and FDM 3D Printing – Machine (Gr = 16). These results suggest that expert discourse was predominantly anchored in the selection of coating methods and the specific technical context of the fabrication hardware. Furthermore, process-oriented codes specifically Selection Factor and Sanding exhibited strong emphasis, whereas parameter-specific settings yielded lower frequencies. Collectively, this distribution reveals that the experts prioritized the execution of finishing techniques and material determinants over granular parameter adjustments, highlighting these as the most critical operational factors in achieving desired surface outcomes.

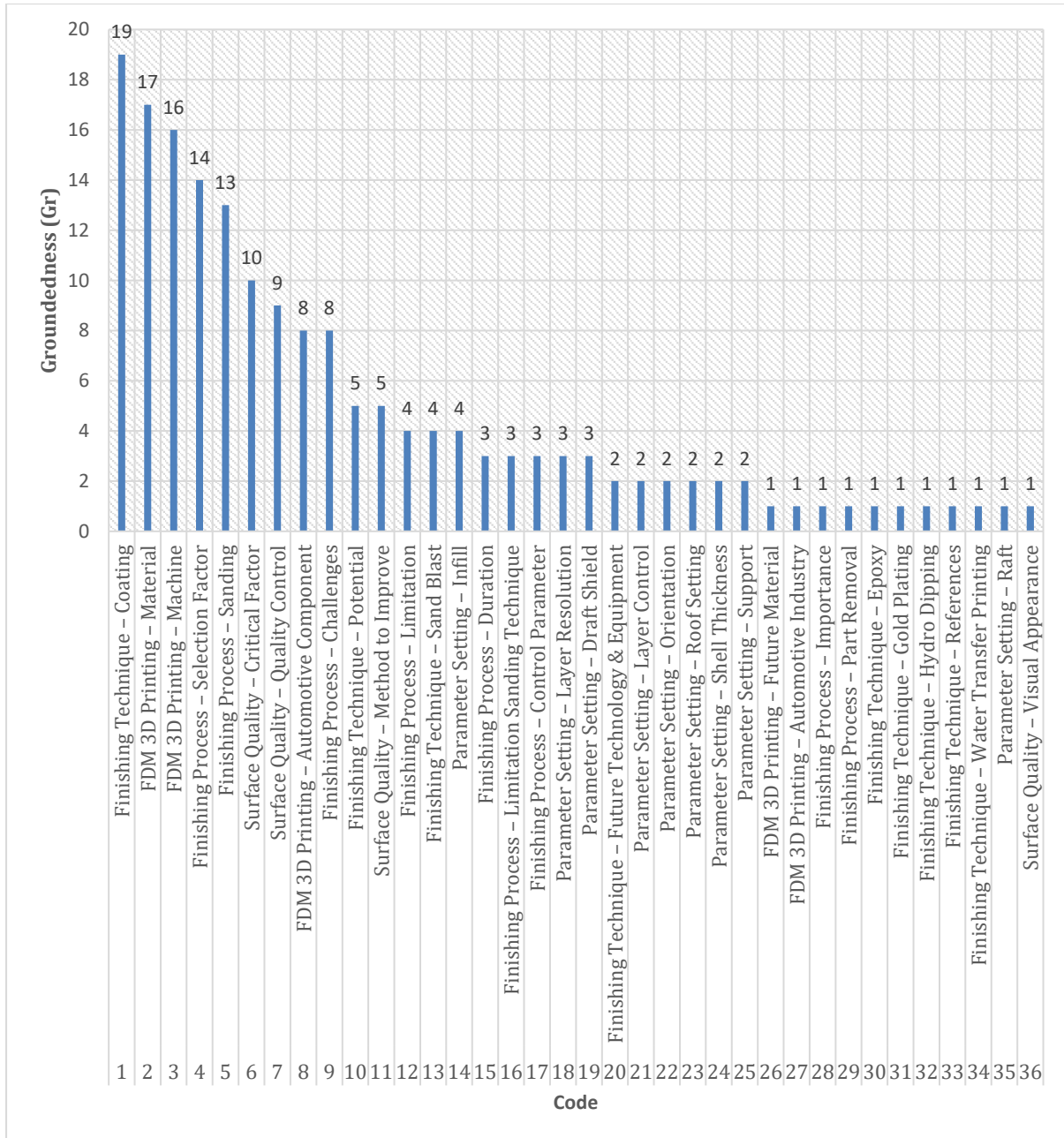


Figure 1: Frequency Distribution of Code Based on Groundedness.

3.2 Code network analysis

To illustrate the complex interactions within the Fused Deposition Modeling (FDM) fabrication and finishing lifecycle, a qualitative code network analysis was conducted using ATLAS.ti. Code Network Analysis is a powerful bibliometric and qualitative technique that maps the conceptual structure of a research field by treating keywords or thematic codes as nodes and their co-occurrences as links [20]. By calculating metrics such as centrality and density, researchers can identify dominant themes, emerging trends, and the degree of interconnectedness within a specific domain. While groundedness (frequency) and density (connectivity) provide essential quantitative indicators, a structural examination of the code network is necessary to reveal how these technical considerations relate. This approach visualizes the precise interdependencies among the pre-processing parameters, post-processing techniques, and surface quality outcomes. By revealing these relational patterns, the network analysis enables the robust abstraction of individual descriptive codes into higher-level thematic domains.

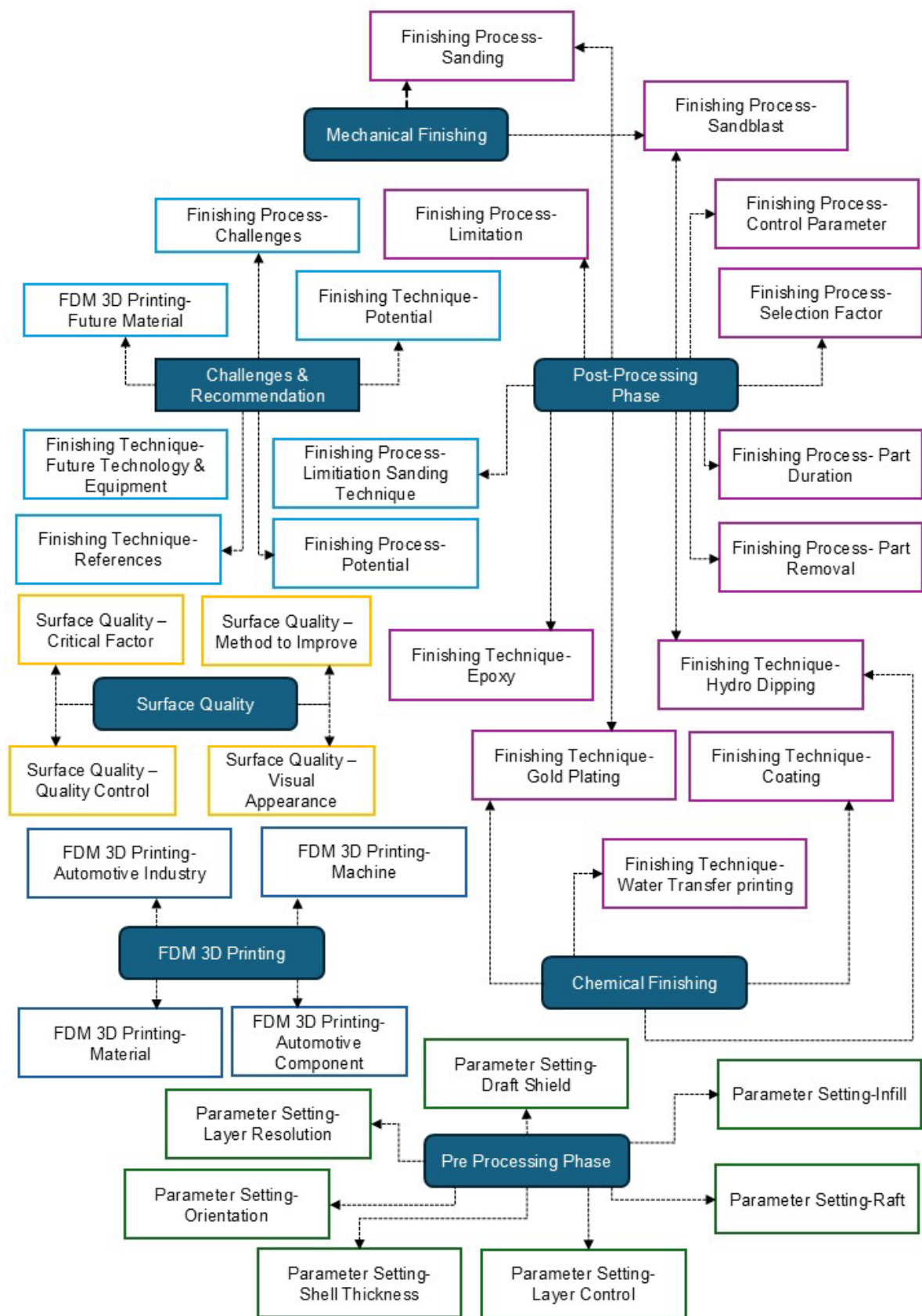


Figure 2: Code network analysis diagram.

Figure 2 graphically details this conceptual network, illustrating how fabrication context (Material, Machine), parameter settings, and specific finishing methodologies converge to determine the final component quality.

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 Theme Development

Theme development was systematically derived through the integration of groundedness (Gr) and code network analyses, ensuring that both frequency-based importance and structural relationships were comprehensively captured. Groundedness analysis identified frequently occurring concepts, such as coating techniques, reflecting strong expert emphasis within the dataset. In parallel, network density (Gs) analysis revealed the strength of interconnections among codes, highlighting the structural roles of different elements within the finishing system. While high-frequency codes, particularly those related to chemical finishing and material-machine factors, indicated areas of dominant expert focus, the network analysis demonstrated that importance cannot be inferred solely from frequency. For instance, the pre-processing phase exhibited moderate groundedness but strong relational connectivity, indicating its critical role as a structural enabler within the finishing workflow. Similarly, surface quality-related codes occupied a central position within the network, reinforcing their role as the primary evaluative outcome of the system. Accordingly, theme abstraction was guided by a multi-dimensional analytical approach that integrates conceptual emphasis (groundedness), structural interdependencies (network density and relationships), and functional relevance within the finishing lifecycle. Through this systematic filtering and abstraction process, six key themes were identified, representing the principal dimensions underpinning the development of the FDM questionnaire.

As shown in Table 4, the thematic structure illustrates the relationships among identified themes, their supporting codes, and their respective strengths based on groundedness (Gr) and density (Gs). The theme Surface Finish Duration demonstrates moderate importance, indicating that aspects such as process duration, limitations, and overall significance are consistently acknowledged but not dominant. In contrast, Factors Influencing Quality exhibits high groundedness and moderate connectivity, highlighting the strong influence of material

properties, machine parameters, and application context on surface outcomes. The Surface Finishing Process emerges as the most critical theme, showing the highest levels of both groundedness and network connectivity, thereby underscoring the central role of process-related activities such as sanding, parameter control, and process challenges in achieving the desired surface quality. Furthermore, a clear distinction is observed between Mechanical Finishing and Chemical Finishing. Mechanical techniques are moderately important, with relatively lower relational connectivity, suggesting more isolated or technique-specific applications. Conversely, chemical finishing methods exhibit higher groundedness and stronger integration within the finishing system, reflecting their broader applicability and influence. Ultimately, Surface Quality is positioned as the central outcome theme, encompassing critical factors, quality control, improvement methods, and visual appearance. This central positioning reinforces its role as the primary performance indicator that integrates and reflects the effectiveness of all preceding finishing-related factors.

Thus, the development of themes was not arbitrary but systematically derived through an analytical filtering process that preserved clear traceability from raw transcript data to higher-level conceptual domains. Each identified theme was subsequently operationalized into a corresponding criterion, ensuring that only empirically grounded and structurally significant factors were carried forward into the consensus validation stage.

Table 4: Themes and supporting code.

Theme	Linked Codes	Metric Strength
Surface Finish Duration	Finishing Process – Duration Finishing Process – Limitation Finishing Process – Importance	Moderate (Gr)
Factors Influencing Quality	FDM 3D Printing – Material FDM 3D Printing – Machine FDM 3D Printing – Automotive Component Finishing Process – Selection Factor	High (Gr) and Moderate (Gs)
Surface Finishing Process	Finishing Process – Sanding Finishing Process – Challenges Finishing Process – Control Parameter Finishing Process – Part Removal	Highest (Gr) and (Gs)
Mechanical Finishing	Finishing Technique – Sand Blast Finishing Process – Limitation Sanding Technique	Moderate (Gr) and Low (Gs)
Chemical Finishing	Finishing Technique – Coating Finishing Technique – Epoxy Finishing Technique – Hydro Dipping Finishing Technique – Gold Plating	High (Gr) and Moderate (Gs)
Surface Quality	Surface Quality – Critical Factor Surface Quality – Quality Control Surface Quality – Method to Improve Surface Quality – Visual Appearance	Central Positioning

3.4 Post-processing criteria identification

The identified themes were systematically operationalized into measurable criteria to enable structured evaluation and facilitate their integration into the subsequent quantitative phase. This stage represents a critical methodological transition from qualitative abstraction to quantitative

validation, ensuring that insights derived from expert consensus are translated into actionable and assessable dimensions. Each of the six themes was retained as a distinct evaluative domain and transformed into a corresponding criterion, preserving both its conceptual meaning and analytical significance. As summarized in Table 5, this transformation provides a clear, traceable linkage between the qualitative findings and the criteria used for consensus validation.

Table 5: Theme to Criteria.

Theme	Criteria Focus
Surface Finish Duration	Importance of time efficiency and process feasibility
Factors Influencing Quality	Influence of material and machine characteristics
Surface Finishing Process	Significance of workflow structure and control
Mechanical Finishing	Importance of preparatory surface smoothing
Chemical Finishing	Influence of coating-based enhancement techniques
Surface Quality	Critical visual and acceptance indicators

Each criterion reflects the functional role of its corresponding theme within the FDM surface finishing system, ensuring that both process-oriented and outcome-driven aspects are captured. The surface finish duration criterion emphasizes time efficiency and process feasibility, highlighting the importance of practical implementation constraints. The factors influencing quality criterion represent upstream determinants, particularly material and machine characteristics, which define the initial condition of printed parts and subsequently affect finishing performance. The surface finishing process criterion serves as the core operational dimension, focusing on workflow structure, control, and repeatability to ensure consistency in outcomes. Mechanical finishing is positioned as a preparatory criterion, contributing to initial surface smoothing and enabling subsequent treatments, whereas chemical finishing functions as the primary enhancement mechanism, significantly influencing surface smoothness, gloss, and visual uniformity. Finally, the surface quality criterion represents the ultimate evaluative domain, encompassing visual appearance and acceptance requirements, and serving as the convergence point of all preceding processes. Collectively, these criteria demonstrate that FDM surface finishing operates as an integrated and interdependent system, where each dimension contributes to achieving the desired aesthetic and functional quality, thereby providing a robust foundation for subsequent quantitative validation and framework development.

4 CONCLUSION

This study systematically identifies and structures critical post-processing criteria through an integrated groundedness–network analytical approach, establishing a preliminary evidence-based foundation for enhancing surface finish consistency in fused deposition modeling (FDM) automotive applications. The analysis demonstrates that surface finishing constitutes an integrated system in which success relies on the synergy between upstream printing parameters and downstream finishing methods. By connecting qualitative insights with quantitative metrics, six core pillars are established: Temporal Efficiency, Capability Compatibility, Process Control, Mechanical Preparation, Chemical Refinement, and Objective Surface Quality. These findings provide a traceable pathway for industry practitioners to advance beyond trial-and-error approaches toward standardized, repeatable outcomes. This research establishes the groundwork for broader adoption of FDM in automotive manufacturing, ensuring that 3D-printed components meet the rigorous aesthetic and functional requirements of the global automotive market.

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Declaration of Generative AI Use

In this work, the authors utilized AI tool to assist with initial literature exploration and to structure the research framework. The authors subsequently conducted a full review, validated all sources, and take full responsibility for the final intellectual content.