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Nikita Tarasov

nikita.a.tarasov@lpnu.ua

Lviv Polytechnic National University

Orest Khamula

Lviv Polytechnic National University

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A Decision-Support Framework for Selecting Braille Formation Technologies in Universal Access Systems

Nikita Tarasov[1,1*] and Orest Khamula[1,2]

[1*]Lviv Polytechnic National University, Lviv, 79000, Ukraine.

*Corresponding author(s). E-mail(s): nikita.a.tarasov@lpnu.ua;
Contributing authors: orest.h.khamula@lpnu.ua;

Abstract

The practical accessibility of tactile information for people with visual impairments is determined not only by the availability of content, but also by the technology of its physical reproduction in a specific institutional context. The presence of several technological approaches to Braille formation does not simplify the choice in practical conditions, but on the contrary complicates it due to the need to simultaneously take into account geometric, organizational, and resource constraints.

This article develops an analytical model for decision support focused on the tasks of preliminary selection of Braille font formation technology in conditions of limited data. The model combines the Analytic Hierarchy Process (AHP) and fuzzy logic, which formalizes linguistic assessments and reduces the influence of subjective interpretation in the scenario-based comparison of alternatives. The proposed hierarchy of criteria covers geometric compliance with Braille standards, technological stability, economic and organizational constraints, as well as factors related to the practical accessibility of application.

The model's performance is illustrated through scenario analysis of typical contexts of use without involving physical experiments. All stages of the calculations were implemented in a reproducible computing environment based on Python and Google Colab. The results demonstrate increased stability of the selection procedure when using a fuzzy multi-criteria decision model. The proposed approach is suitable for use as an analytical tool for the preliminary selection of technologies in the field of accessible and inclusive solutions.

Keywords: Braille; tactile graphics; assistive technology; universal access; multi-criteria decision-making; AHP; fuzzy logic; additive manufacturing

1 Introduction

Universal access to information for people with visual impairments is impossible without stable and predictable access to tactile materials. In educational environments, the quality of the raised dot font directly affects reading speed, perceptual accuracy, and cognitive load, while in navigation applications it directly affects the safety and autonomy of users [1, 2]. However, in real-world institutional settings such as education, rehabilitation, and public infrastructure, decisions regarding the choice of Braille formation technology are often made without a formalized mechanism for comparing available alternatives.

The modern technological landscape encompasses a wide range of approaches to Braille production, including classical embossing and thermoforming methods, digital design workflows, additive manufacturing, and electronic tactile displays [3–5]. Each of these technologies exhibits specific advantages and limitations related to geometric accuracy, relief durability, preparation speed, cost, and infrastructure requirements. As a result, no single approach can be considered universally optimal, and the selection process inevitably involves trade-offs between quality, accessibility, and flexibility of application.

For Braille, strict adherence to the geometric structure of the basic cell is critical, as parameters such as dot height, dot diameter, and inter-dot spacing determine tactile recognition and readability [6]. These geometric characteristics form the perceptual foundation of Braille reading and must be preserved regardless of the underlying production technology.

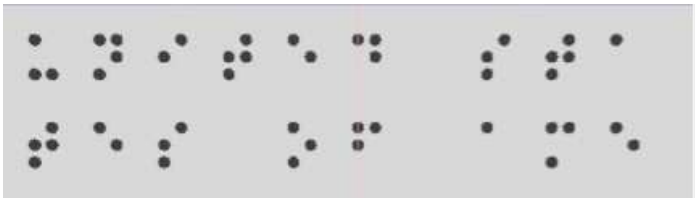


Fig. 1 Structure of a basic Braille cell.

Figure 1 illustrates the standardized structure of a basic Braille cell, consisting of six tactile dots arranged in a two-column by three-row matrix. Compliance with this structure is essential not only for textual Braille but also for tactile maps, spatial schemes, and complex graphical representations, where the informational value of the relief depends strongly on the selected formation technology [7].

Existing studies describe traditional Braille production methods as reliable and suitable for mass reproduction, yet limited in terms of adaptability and customization [3, 5]. Electronic tactile displays provide dynamic access to content but remain constrained by high cost and limited display area [8, 9]. Additive manufacturing enables individualized tactile artifacts and complex relief geometries; however, it is sensitive to printing parameters, materials, and post-processing procedures, which directly affect the reproducibility and durability of tactile features [10, 11].

Research on inclusive design increasingly emphasizes the necessity of evaluating assistive technologies not only by their physical characteristics but also by organizational and resource-related constraints of specific application contexts. These include requirements for scalability, repeatability, and long-term use in educational materials and public tactile infrastructure [12, 13]. In practice, however, the choice of Braille formation technology is often performed in a fragmented manner—based on isolated parameters or local experience—without a transparent structure for comparing trade-offs or reproducing the decision-making process.

Although multi-criteria decision-making (MCDM) methods, including AHP and fuzzy extensions, have been applied to the selection of individual assistive devices, existing models rarely address the entire spectrum of Braille rendering technologies within a single analytical framework [14–16]. This limitation reduces the ability of institutions to justify technology choices for specific use cases.

This paper proposes a reproducible decision-support framework for prioritizing Braille formation technologies in the context of universal access. The approach integrates the Analytic Hierarchy Process and fuzzy logic to model uncertainty and the linguistic nature of expert evaluations. Four key criteria—relief quality and durability, cost and availability, development flexibility, and preparation speed—are structured within the model and applied to seven representative technological alternatives.

The evaluation is conducted in the form of scenario-based analytical analysis at the technology selection stage, without performing laboratory or physical experiments. All computations are implemented in a reproducible Python-based environment using Google Colab, enabling adaptation of the model to different institutional contexts and assessment of result stability. This work focuses on comparative technology selection rather than optimization of a specific production process.

2 Related Work

Research in the field of Braille embossing encompasses a wide range of technological approaches that differ in embossing principles, achievable geometric accuracy, infrastructure requirements, and suitability for specific application scenarios. However, the majority of existing publications focus on individual classes of technologies in isolation, without providing a unified analytical comparison oriented toward practical decision-making in institutional contexts.

2.1 Classical Embossing and Thermoforming

Classical Braille embossing methods, including mechanical embossing and thermoforming, remain the dominant solutions in educational and industrial environments. Mechanical embossing systems, ranging from desktop to industrial-scale devices, provide stable embossing geometry and high material durability, which is critical for mass reproduction of educational materials [3, 5]. Their primary advantage lies in repeatability and long-term resistance to mechanical wear.

Thermoforming is widely used for the production of tactile maps, diagrams, and reusable educational media. Its key advantage is the reproducibility of tactile relief after the creation of a physical master matrix. At the same time, the requirement

to manufacture such matrices significantly limits flexibility and makes the technology unsuitable for rapid individualization or frequent content updates [4, 17]. Most studies consider mechanical embossing and thermoforming separately, without quantitative comparison with alternative technologies.

2.2 Electronic Braille Displays

Electronic tactile displays form a distinct technological class focused on providing dynamic access to digital content. Contemporary solutions rely on piezoelectric or electromechanical actuators to generate miniature tactile relief synchronized with electronic information sources [8, 9]. Research in this domain primarily addresses actuator optimization, energy efficiency, and cost reduction [18, 19].

Despite their advantages in content variability, electronic tactile displays suffer from systemic limitations, including high device cost, limited tactile output area, and difficulties in scaling to large-format tactile structures. Consequently, they are rarely considered as a full-fledged alternative to physical relief generation in educational or navigation scenarios, where spatial tactile representations play a central role [8, 20].

2.3 CAD Modelling and Digital Preparation

Digital design has become a fundamental stage in the modernization of Braille formation processes. Computer-aided design (CAD) systems enable precise control of key geometric parameters of the Braille cell, including dot height, dot diameter, and inter-dot spacing, in accordance with established readability standards [21, 22]. Such models are employed both for digital tactile prototyping and as a preparatory stage for additive manufacturing.

Several works propose formalized approaches for evaluating tactile graphic elements and their geometric consistency [23, 24]. However, most studies remain focused on technical accuracy of geometric models, while the integration of the CAD stage into multi-criteria frameworks for technology selection—considering cost, preparation time, and operational constraints—remains insufficiently developed.

2.4 Additive Manufacturing

Additive manufacturing has opened up the possibility of creating complex tactile structures that are inaccessible to traditional methods [10, 17]. In the context of Braille formation, FDM and SLA/DLP technologies are most often used [25].

FDM printing provides accessibility and ease of operation, but can lead to variability in relief height and surface layering [21]. SLA/DLP technologies, on the contrary, provide high accuracy of dot formation, which is critically important for complex tactile models [11].

In particular, marking methods and creation of audio-tactile resources are being developed that combine printed models with information labels [12, 26]. However, most research on additive manufacturing focuses on optimizing printing parameters or accuracy of dot geometry [25, 27]. They do not provide a broader comparison with alternative terrain generation technologies, which complicates decision-making in

practical scenarios—for example, in educational institutions, where not only accuracy but also speed of preparation, cost, and regulatory compliance are important.

The quality of Braille relief is evaluated for various technologies, including UV inkjet printing, where dot geometry control is required [28]. In research, the quality of Braille relief for additive technologies is often described in terms of generalized functional dependencies on technological parameters, in particular layer height, extrusion stability, material properties and temperature conditions [11, 29]. This relationship can be expressed in a generalized form as follows:

$$R_{\text{tactile}} = f(h_{\text{layer}}, S_{\text{extr}}, M, T), \tag{1}$$

where h_{layer} denotes the layer height, S_{extr} represents extrusion stability, M characterizes material properties, and T corresponds to the temperature regime.

Most existing studies in this area focus on parameter optimization or geometric accuracy in isolation and do not provide a systematic comparison with alternative Braille formation technologies. This limits their applicability for practical decision-making in educational institutions, where accuracy must be balanced against preparation speed, cost, and regulatory compliance.

2.5 Manual Braille Methods

Manual Braille generation methods, particularly Slate & Stylus, remain among the most accessible and autonomous tools for visually impaired users. Their principal advantages include low cost, portability, and independence from technical infrastructure [30]. However, manual Braille production is characterized by low repeatability and strong dependence on user skill, which significantly restricts its use for large-scale preparation of educational materials.

2.6 Comparative Structure of Braille Formation Technologies

To summarize the existing approaches, the primary Braille formation technologies are presented in a structured comparative form in Table 1. The comparison highlights the trade-offs between durability, flexibility, cost, and preparation speed that are insufficiently addressed in existing descriptive studies.

Table 1 Comparison of Braille formation technologies

Technology	**Strengths**	**Limitations**
Mechanical embossing	Durable relief, high stability	High cost, limited adaptability
Slate & Stylus	Accessibility, autonomy	Low speed, skill-dependent quality
Electronic displays	Dynamic tactile output, mobility	Limited output area, high cost
CAD modelling	High geometric accuracy, scalability	Requires technical expertise
Tactile ink printing	Rapid preparation	Low durability of relief
Thermoforming	Mass production, high repeatability	Requires physical matrices
3D printing	Individualization, complex geometries	Long preparation time

A comparative analysis of the reviewed literature demonstrates that most existing studies remain descriptive and do not employ multi-criteria decision-making methods capable of handling uncertainty in expert assessments. This limitation reduces their suitability for practical technology selection in the context of universal access systems and motivates the development of a generalized quantitative framework combining the strengths of AHP and fuzzy logic.

3 Research Gap and Problem Statement

3.1 Research Gap

The analysis shows that research in the field of Braille development mainly focuses on individual classes of technologies without systematically comparing them in a single analytical space. Such works provide valuable technical information, but do not offer tools for consistent comparison of alternatives taking into account different scenarios of practical application.

Existing multi-criteria approaches, in particular AHP and its fuzzy modifications, are mainly used for the selection of individual assistive devices or production processes, without covering a systematic comparison of alternatives in the field of tactile and inclusive technologies [31, 32]. In addition, evaluation criteria are often considered in isolation—with a focus only on accuracy or cost—without integrating the parameters of tactile readability, economic constraints, and development flexibility.

A separate problem is the uncertainty of evaluation inherent in the scenario-analytic comparison of assistive technologies. Most works use rigid numerical scales that do not reflect the variability of interpretations and contextual constraints, which reduces the practical value of the results.

3.2 Problem Statement

Given the above gaps, there is a need for a formalized decision-support system capable of comparing different technologies for the formation of relief-dotted Braille according to agreed criteria in conditions of limited or incomplete empirical information. The problem is not the lack of technologies, but the lack of a transparent mechanism for choosing between them in specific educational and institutional scenarios.

This work addresses the problem of prioritizing seven major technologies for Braille formation by integrating the Analytic Hierarchy Process (AHP) and fuzzy logic into a single multi-criteria model. The proposed approach enables: (1) structuring selection criteria related to relief quality, preparation speed, cost, and development flexibility; (2) formalizing linguistic assessments that reflect uncertainty in scenario-based comparisons; and (3) obtaining a quantitative, reproducible ranking of technologies without the need for full-scale physical experiments.

Unlike previous works, the proposed model does not focus on optimizing a single technology, but provides a generalized analytical framework for comparing traditional, manual, electronic, and additive approaches within a unified methodological field. Thus, the novelty of the study lies in the transition from fragmentary technological

assessments to an explanatory, scenario-oriented decision-support system relevant to universal access and inclusive design tasks.

Figure 2 illustrates the conceptual structure of Braille formation technologies and their relationship with key selection factors. Within the model, the considered technologies are grouped into four classes: traditional mechanical methods, manual tools, digital and additive technologies, and electronic tactile displays.

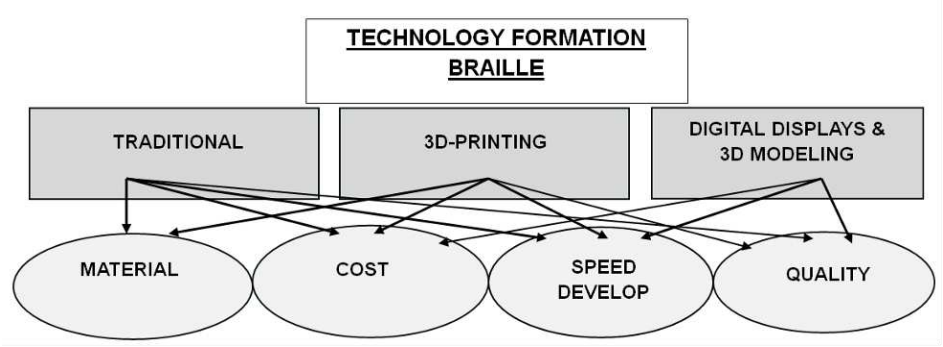


Fig. 2 Conceptual framework of Braille formation technologies and their classification.

Each class of technologies is associated with a set of characteristics that determine practical suitability, including relief quality and durability, preparation speed, cost, and availability of infrastructure, and flexibility of content development and adaptation. The conceptual scheme demonstrates that no technology provides optimal values for all criteria simultaneously, and the choice inevitably involves trade-offs between accuracy, economic constraints, and usage scenarios.

Thus, Figure 2 serves as an analytical bridge between the review of existing technologies and a formalized multi-criteria evaluation model, justifying the feasibility of using the AHP–Fuzzy approach for a structured comparison of alternatives considering the uncertainty of expert assessments.

4 Methodology: AHP–Fuzzy Multi-Criteria Evaluation Framework

4.1 Methodological Overview

The proposed study aims to support decision-making regarding the selection of technologies for generating raised-dot Braille within universal access systems. The methodology is explicitly focused on the *design-time* decision-making stage, in which physical prototyping or experimental validation is limited, unavailable, or economically impractical. Such conditions are typical for educational institutions, rehabilitation centers, and low-resource environments.

The evaluation does not rely on newly collected empirical measurements or user-centered experimental studies. Instead, it synthesizes evaluation criteria derived from established standards, expert-oriented research, and technological configurations

reported in peer-reviewed literature. This approach is consistent with analytical decision-support models commonly applied in accessibility engineering, where transparency, explainability, and reproducibility are prioritized over laboratory-scale experimentation.

Given the multi-criteria nature of the problem and the inherent uncertainty associated with expert judgments, the methodology integrates the Analytic Hierarchy Process (AHP) [33] with fuzzy linguistic evaluation of alternatives. This integration enables the formalization of subjective assessments while preserving interpretability and ensuring traceability of the ranking process [34–36].

The overall evaluation workflow consists of the following sequential stages:

1. formation of a hierarchical structure comprising the decision goal, evaluation criteria, and technological alternatives;
2. determination of criteria weights using the AHP method;
3. scenario-based evaluation of alternatives using fuzzy numbers;
4. defuzzification and weighted aggregation of evaluation results;
5. sensitivity analysis and visualization of the final rankings.

4.2 Hierarchical Structure of the Decision Model

The hierarchical structure of the decision model is defined across three conceptual levels:

- **Goal**: selection of the optimal technology for forming raised-dot Braille;
- **Evaluation criteria**:
  - C_1: quality and durability of the tactile relief;
  - C_2: speed of material preparation;
  - C_3: cost and availability of the technology;
  - C_4: design flexibility and adaptability.
- **Technological alternatives**: mechanical embossing, thermoforming, electronic Braille displays, manual methods (Slate & Stylus), CAD-based modeling, additive manufacturing using FDM, and additive manufacturing using SLA/DLP.

This hierarchical formulation enables systematic comparison of Braille formation technologies without privileging a single dominant parameter. Instead, it explicitly captures trade-offs between technical performance, economic constraints, and operational flexibility, which are essential for informed decision-making in universal access systems.

4.3 Criteria Weight Determination Using AHP

At the first stage, the relative importance of the evaluation criteria is determined using the Analytic Hierarchy Process (AHP) proposed by Saaty [33]. For this purpose, a pairwise comparison matrix is constructed using the nine-point fundamental scale of relative importance.

Let $\mathbf{A} = [a_{ij}]$ denote the pairwise comparison matrix, where a_{ij} represents the relative importance of criterion i compared to criterion j. The matrix normalization

is performed column-wise according to the following expression:

$$a_{ij}^{\text{norm}} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \tag{2}$$

where n is the number of criteria.

The weight vector of the criteria is then computed as the average value of the normalized elements in each row:

$$w_i = \frac{1}{n} \sum_{j=1}^{n} a_{ij}^{\text{norm}}, \tag{3}$$

where w_i denotes the weight of the i-th criterion.

To verify the logical consistency of expert judgments, the consistency ratio (CR) is evaluated based on the consistency index (CI) and the random index (RI). A value of CR < 0.1 is considered acceptable and indicates sufficient logical consistency of the pairwise comparison matrix.

4.4 Fuzzy Evaluation of Alternatives

Since the evaluation of technological alternatives with respect to the selected criteria involves uncertainty and cannot be adequately expressed using precise numerical values, fuzzy linguistic assessment is employed. The study applies triangular fuzzy numbers followed by defuzzification to represent expert judgments [34, 37].

Each evaluation of alternative A_i under criterion C_j is represented as a triangular fuzzy number:

$$\widetilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}), \tag{4}$$

where l_{ij}, m_{ij}, and u_{ij} correspond to the lower bound, the most probable value, and the upper bound of the assessment, respectively. Linguistic terms such as *low*, *medium*, and *high* are mapped onto predefined fuzzy intervals.

In cases where multiple scenario interpretations or independent sources of evaluation are available, aggregation of fuzzy assessments is performed using the geometric mean:

$$\widetilde{a}_{ij}^{\text{agg}} = \left(\prod_{k=1}^{N} l_{ij}^{(k)} \right)^{\frac{1}{N}}, \left(\prod_{k=1}^{N} m_{ij}^{(k)} \right)^{\frac{1}{N}}, \left(\prod_{k=1}^{N} u_{ij}^{(k)} \right)^{\frac{1}{N}} \tag{5}$$

where N is the number of evaluation sources.

This aggregation approach preserves the shape of the fuzzy interval and avoids artificial reduction of uncertainty, which is essential for scenario-based analytical comparison of assistive technologies.

4.5 Defuzzification and Aggregation

To transform fuzzy linguistic evaluations into comparable numerical values, the centroid (center of gravity) defuzzification method is applied. For each triangular fuzzy

number $\widetilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, the defuzzified value is computed as:

$$D(\widetilde{a}_{ij}) = \frac{l_{ij} + 4m_{ij} + u_{ij}}{6}. \tag{6}$$

This method provides a balanced representation of the fuzzy estimate by assigning higher importance to the most probable value while preserving the influence of uncertainty bounds.

The integral priority of each alternative A_i is then calculated as the weighted sum of the defuzzified evaluations:

$$P_i = \sum_{j=1}^{n} w_j \cdot D(\widetilde{a}_{ij}), \tag{7}$$

where w_j denotes the weight of the j-th criterion obtained from the AHP procedure, and n is the number of evaluation criteria.

The resulting value P_i reflects the relative suitability of each technology within the defined decision scenario and serves as the basis for the final ranking of alternatives.

4.6 Computational Workflow and Reproducibility

All analytical calculations were performed in a fully reproducible computational environment based on Python using Jupyter and Google Colab notebooks. The computational workflow includes the following sequential stages:

1. formation of the hierarchical decision structure;
2. computation of criteria weights using the AHP method;
3. generation of fuzzy linguistic evaluations for alternatives;
4. defuzzification and weighted aggregation of results;
5. sensitivity analysis and visualization of final rankings.

Google Colab is employed as a tool to ensure transparency, traceability, and reproducibility of analytical calculations rather than as an environment for physical experimentation. The complete computational notebook, including all input matrices, fuzzy evaluation tables, and visualization scripts, is provided as supplementary material.

The methodology is based on the sequential integration of Saaty's hierarchical analysis [33] and triangular fuzzy numbers [37]. The proposed Fuzzy-AHP framework follows established practices in multi-criteria process optimization, including applications in additive manufacturing and 3D printing [38].

In the present study, seven technological alternatives and four evaluation criteria are considered: quality and durability of the tactile relief, preparation speed, cost and affordability, and development flexibility. Accordingly, the methodological framework consists of two complementary stages: (1) determination of criteria weights using the Analytic Hierarchy Process, and (2) evaluation of alternatives using triangular fuzzy numbers within the Fuzzy AHP model [34, 35, 39]. This integration enables a

structured representation of criterion importance while mitigating uncertainty inherent in expert assessments, thereby improving the robustness and interpretability of the decision-support process [36].

a. Hierarchical Structure

In the first step, a hierarchical structure of the model is formed (Figure 3), which includes the goal, criteria, and alternatives:

- **Goal**: selection of the optimal technology for forming a relief-dot font;
- **Criteria**: relief quality, development speed, cost, flexibility;
- **Alternatives**: mechanical embossing, slate & stylus, electronic devices, CAD modeling, ink tactile printing, thermoforming, 3D printing (FDM/SLA).

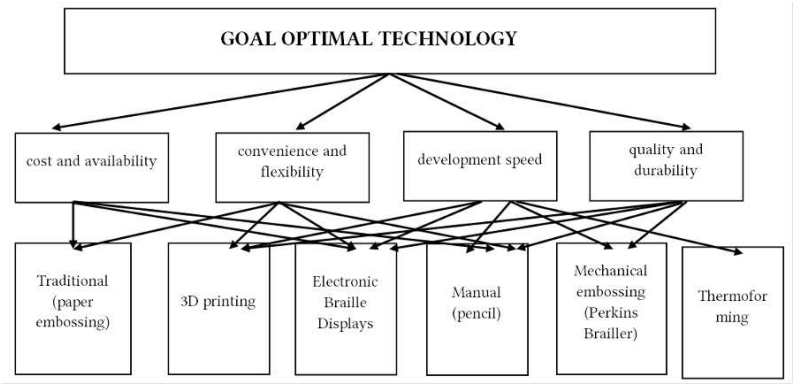


Fig. 3 Hierarchical structure of the AHP–Fuzzy evaluation model

This structure will determine for us how further comparisons are performed.

Pairwise Comparison (AHP)

The matrix of pairwise comparisons of criteria was formed on the basis of analytically generalized assessments using the Saaty scale (Table 2).

Table 2 Pairwise comparison matrix of evaluation criteria constructed using the Saaty scale (1–9)

Criteria	**Quality and durability**	**Preparation speed**	**Cost and accessibility**	**Development flexibility**
Quality and durability	1	5	3	3
Preparation speed	1/5	1	1/3	1/2
Cost and accessibility	1/3	3	1	2
Development flexibility	1/3	2	1/2	1

The matrix of comparisons of criteria is formed according to the Saaty scale (1–9) [33]:

$$\mathbf{A} = \begin{bmatrix} 1 & 5 & 3 & 3 \\ \frac{1}{5} & 1 & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{3} & 3 & 1 & 2 \\ \frac{1}{3} & 2 & \frac{1}{2} & 1 \end{bmatrix}. \tag{8}$$

Normalization and the weight vector:

$$a_{ij}^{\text{norm}} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \tag{9}$$

$$\omega_i = \frac{1}{n} \sum_{j=1}^{n} a_{ij}^{\text{norm}}. \tag{10}$$

After normalization and averaging:

$$\mathbf{W} = [0.5071,\ 0.0838,\ 0.2583,\ 0.1508]\,. \tag{11}$$

The resulting weight vector corresponds to the order of the criteria defined in Table 2: Quality and durability, Speed of preparation, Cost and availability, Flexibility of development.

To check the consistency, we use the formula:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(A\boldsymbol{\omega})_i}{\omega_i \cdot n}. \tag{12}$$

Consistency Index:

$$CI = \frac{\lambda_{\max} - n}{n - 1}. \tag{13}$$

$$CI = \frac{4.1817 - 4}{3} = 0.0606. \tag{14}$$

Consistency Ratio:

$$CR = \frac{CI}{RI}. \tag{15}$$

$$CR = \frac{0.0606}{0.90} \approx 0.067. \tag{16}$$

where $\lambda_{\max}$ is the largest eigenvalue of the matrix, n is the number of criteria, and RI is the random index (for $n = 4$: $RI = 0.90$). In this study, the value of $CR < 0.10$ was obtained, which indicates acceptable consistency of the matrix and the correctness of the use of weights at the following stages.

4.7 Fuzzy Extension

Since analytically generalized estimates formed on the basis of scientific research, standardized configurations, and scenario assumptions inevitably contain uncertainty, qualitative assessments of technologies are presented in the form of triangular fuzzy numbers [37]. In the case of using several scenario interpretations, the assessment is performed by aggregating fuzzy values, where the fuzzy estimates are averaged by the geometric mean [34]. Thus, each alternative assessment is described by a triangular fuzzy number according to the following form:

$$\widetilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}), \tag{17}$$

where l_{ij} is the minimum estimate, m_{ij} is the most typical (modal) estimate, and u_{ij} is the maximum possible estimate.

To formalize qualitative scenario assessments, a linguistic evaluation scale was adopted that reflects typical interpretations of technical characteristics (Table 3). This approach allows uncertainty to be represented in a formalized manner without introducing artificial numerical precision.

Table 3 Linguistic evaluation scale used for scenario-based assessment of Braille formation technologies

Linguistic term	Score range
Very low	0.1
Low	0.3
Medium	0.5
High	0.7–0.8
Very high	0.9–1.0

The criteria weights obtained using the AHP procedure (Table 2) are subsequently combined with expert linguistic assessments of the alternatives (Table 3). This integration enables aggregation of qualitative judgments under uncertainty while preserving the relative importance of criteria defined in the hierarchical decision model (Figure 3).

Aggregation of assessments

If an alternative is evaluated by several experts, their fuzzy estimates are aggregated using the geometric mean [34]:

$$\widetilde{a}_{ij}^{\text{agg}} = \left(\left(\prod_{k=1}^{N} l_k \right)^{1/N}, \left(\prod_{k=1}^{N} m_k \right)^{1/N}, \left(\prod_{k=1}^{N} u_k \right)^{1/N} \right), \tag{18}$$

where N is the number of scenario interpretations or expert assessments.

This aggregation method preserves the proportional structure of the triangular fuzzy interval and avoids artificial reduction of uncertainty.

The generalized fuzzy estimates of the alternatives across all criteria are presented in Table 4. These values are not derived from physical experiments; instead, they represent analytically generated scenario inputs based on standard technological configurations, manufacturer specifications, and findings reported in scientific literature. This is consistent with the design-time nature of the proposed decision-support framework.

Table 4 Scenario-based aggregated fuzzy evaluation scores of seven Braille formation technologies across four criteria

Technology	**Quality**	**Speed**	**Cost**	**Flexibility**
3D printing (FDM)	0.5	0.5	0.7	0.8
3D printing (SLA)	0.8	0.4	0.3	0.8
Electronic displays	0.8	0.9	0.1	0.8
Manual methods	0.5	0.1	0.9	0.5
Mechanical embossing	0.8	0.5	0.5	0.8
Thermoforming	0.8	0.3	0.5	0.3
Traditional embossing	0.8	0.8	0.6	0.8

Defuzzification

To transform fuzzy estimates into numerical values, the centroid defuzzification method is applied:

$$D(\widetilde{a}_{ij}) = \frac{l_{ij} + 4m_{ij} + u_{ij}}{6}. \tag{19}$$

After defuzzification, all alternative scores are weighted using the AHP-derived criteria weights:

$$P_i = \sum_{j=1}^{4} w_j \cdot D\left(\widetilde{a}_{ij}\right). \tag{20}$$

The resulting value P_i represents the integral efficiency of each technology within the considered scenario.

4.8 Computational Workflow and Visualization

All numerical computations, including fuzzy pairwise matrix aggregation, defuzzification, consistency checking, principal component analysis (PCA)–based dimensionality reduction, clustering, and visualization, were performed in a Python-based environment compatible with Jupyter notebooks. The Google Colab runtime was used as the execution platform due to its reproducibility, ease of sharing, and suitability for matrix-intensive operations typical of AHP–Fuzzy models. The complete computational notebook is provided as supplementary material.

The computational workflow corresponds to a reproducible analytical pipeline consisting of the following sequential stages:

1. building a hierarchical structure of the decision problem;

2. forming the pairwise comparison matrix;
3. normalization and computation of AHP criteria weights;
4. generation of fuzzy linguistic evaluations;
5. aggregation of expert or scenario-based fuzzy data;
6. defuzzification of triangular fuzzy numbers;
7. calculation of final priority scores for alternatives;
8. visualization of results (ranking diagrams, heat maps, PCA-based clustering).

The overall computational pipeline of the evaluation procedure is illustrated in Figure 4. The scheme demonstrates the sequence of analytical stages, starting from the formation of the hierarchy of criteria and alternatives and progressing through defuzzification, aggregation of results, and sensitivity analysis. Such a structure ensures transparency of the decision-making process and allows a clear separation of the analytical technology-selection stage from physical experimentation, which is fundamental for design-time decision-support systems.

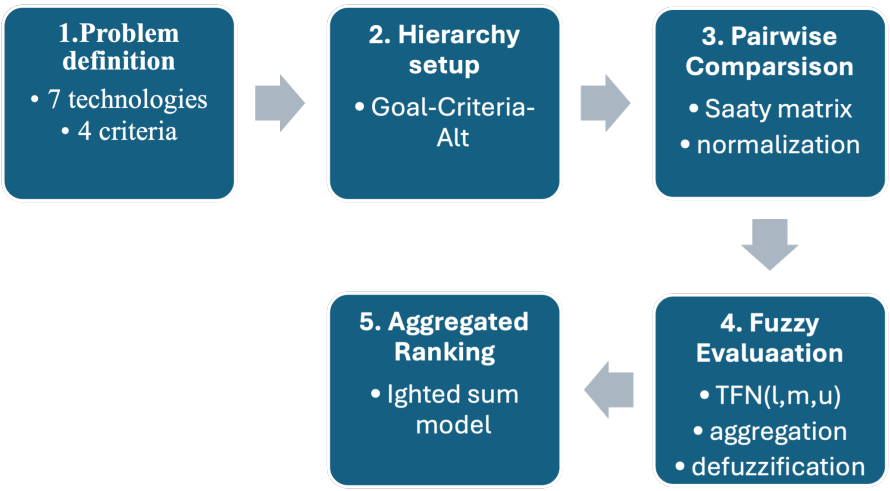


Fig. 4 Computational pipeline for AHP–Fuzzy evaluation.

Based on the obtained results, several visual representations were constructed, including a technology ranking diagram, heat maps of fuzzy evaluations, and sensitivity analysis plots for each criterion.

For visual comparison of alternatives across all criteria, a heat map of fuzzy evaluations was employed (Figure 5). This visualization enables rapid identification of the relative strengths and weaknesses of each technology without reducing the analysis to a single aggregated indicator. Such an approach enhances the interpretability of the results and supports informed decision-making in the context of universal access systems.

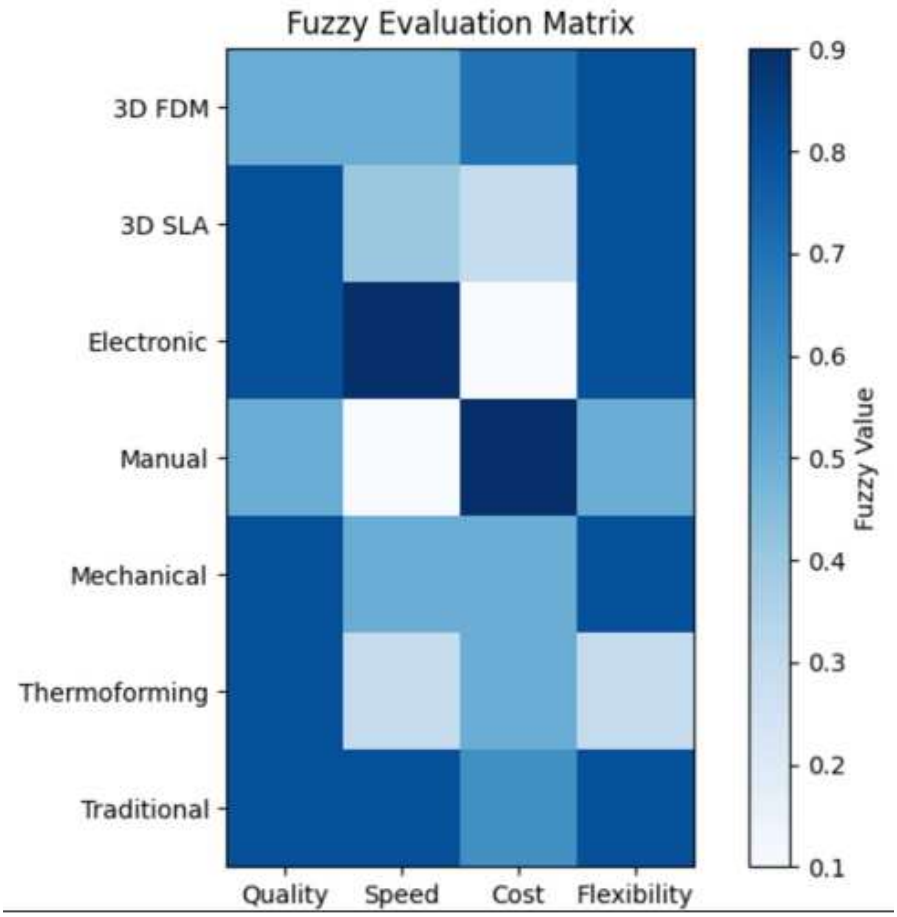


Fig. 5 Heat map of fuzzy evaluations for seven Braille formation technologies across four criteria.

The heatmap visualizes the triangular fuzzy values assigned to each technology for each criterion, where darker color intensities correspond to higher fuzzy scores. The resulting matrix highlights the relative advantages and limitations of technologies such as FDM, SLA, and mechanical embossing across quality, speed, cost, and flexibility dimensions.

5 Results

This section presents the key results obtained using the combined AHP and Fuzzy AHP decision-support model. The analysis includes the derived weights of evaluation criteria, defuzzified priority values of technological alternatives, final rankings, and sensitivity analysis assessing the robustness of the model.

5.1 Criteria Weights

Application of the AHP method revealed a clear dominance of the criterion *Quality and durability of tactile relief*, with a final weight of approximately 0.50. This result is consistent with fundamental Braille requirements, where relief stability and geometric consistency directly determine tactile readability and user perception.

The criterion *Cost and availability* ranked second (approximately 0.26), reflecting realistic economic and infrastructural constraints faced by educational and rehabilitation institutions. *Development flexibility* (approximately 0.16) and *Preparation speed* (approximately 0.08) demonstrated a smaller, yet non-negligible influence on the final decision outcome.

To assess the robustness of the weighting scheme, a sensitivity analysis was performed by varying the weight of each criterion within a range of $\pm 10\%$ while proportionally adjusting the remaining criteria. The sensitivity plots (Figures 6–9) indicate that such variations do not lead to changes in the ordering of the highest-priority alternatives, confirming the stability of the model.

The final normalized weights of the evaluation criteria obtained using the AHP method are summarized in Table 5.

Table 5 Relative importance of evaluation criteria obtained through the AHP-based weighting procedure

Criterion	**Weight**
Quality and durability	0.50
Cost and availability	0.26
Development flexibility	0.16
Preparation speed	0.08

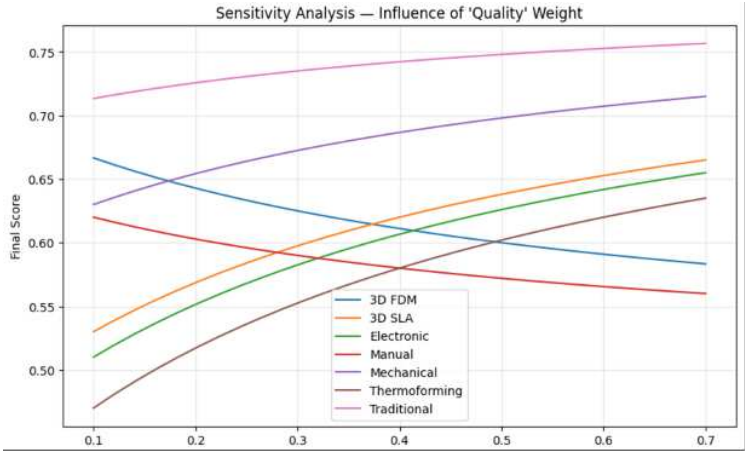


Fig. 6 Sensitivity analysis for the quality and durability criterion.

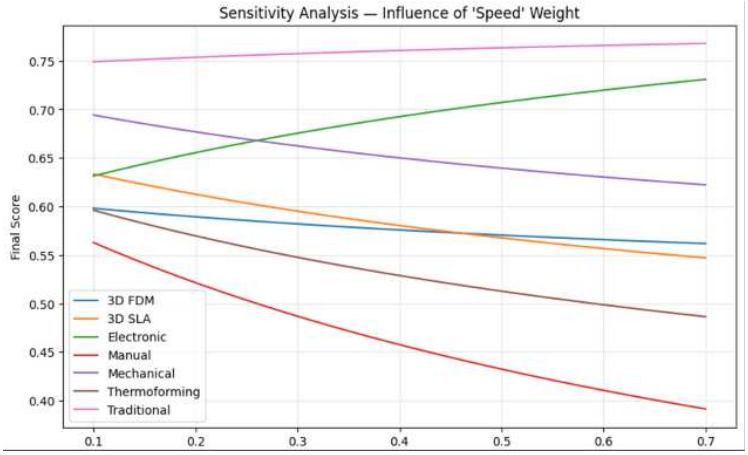


Fig. 7 Sensitivity analysis for the preparation speed criterion.

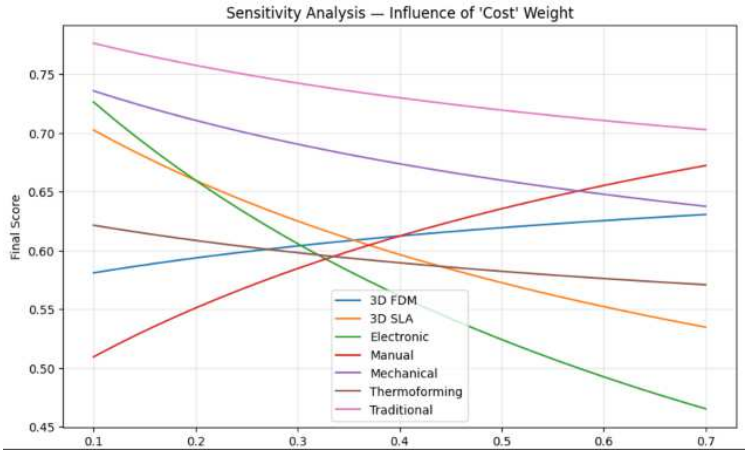


Fig. 8 Sensitivity analysis for the cost and availability criterion.

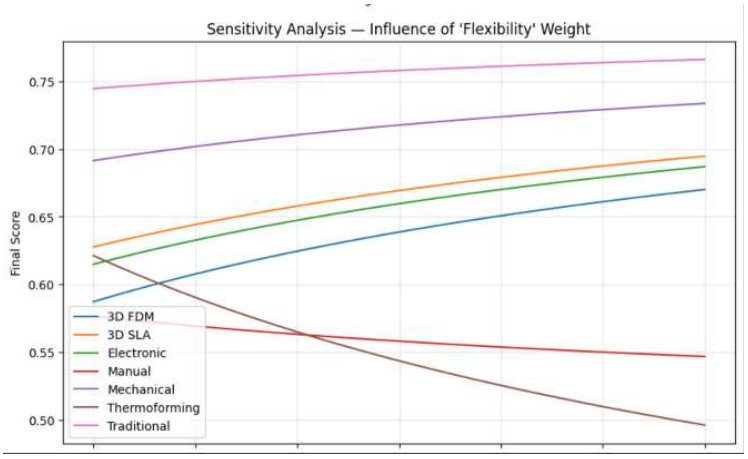


Fig. 9 Sensitivity analysis for the development flexibility criterion.

5.2 Priorities of Technologies

After defuzzification of fuzzy evaluations and weighted aggregation of scores, integral priority values were obtained for all considered technologies. Traditional embossing and mechanical embossing achieved the highest priority values (0.74834 and 0.69737, respectively), which can be attributed to the high stability of tactile relief, minimal variability of dot geometry, and efficient preparation processes.

Among digital methods, SLA/DLP additive manufacturing demonstrated the highest priority value (0.63733), confirming its suitability for applications requiring high geometric accuracy. FDM printing (0.59690) showed a balance between affordability and acceptable tactile quality, albeit with reduced repeatability due to layer-based fabrication. Electronic tactile displays (0.62757) achieved relatively high scores in terms of quality and access speed but were penalized by high cost and limited tactile output area. Manual Braille methods (0.56980) obtained the lowest priority due to low repeatability and slow preparation.

The final defuzzified and aggregated priority values of the evaluated technologies are presented in Table 6.

Table 6 Final priority values of Braille formation technologies after defuzzification and weighted aggregation

Technology	**Priority value**
Traditional embossing	0.74834
Mechanical embossing	0.69737
3D printing (SLA/DLP)	0.63733
Electronic displays	0.62757
Thermoforming	0.60521
3D printing (FDM)	0.59690
Manual methods	0.56980

The final ranking of technologies derived from the aggregated priority values is illustrated in Figure 10. The diagram highlights the trade-offs between relief stability, economic constraints, and development flexibility, confirming the analytical nature of the proposed decision-support model.

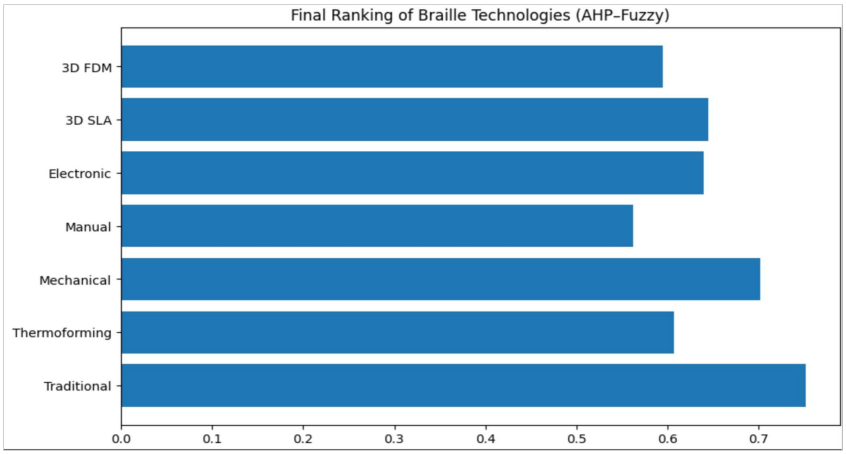


Fig. 10 Final ranking of Braille formation technologies computed from defuzzified fuzzy scores.

5.3 Sensitivity Analysis

Additional analysis confirmed that variations in the weight of the dominant criterion *Quality and durability* do not lead to changes in the relative ranking of alternatives. The largest sensitivity was observed for additive manufacturing technologies (FDM and SLA/DLP); however, these variations remained within bounds that do not affect the ordering of technologies.

Overall, the stability of the rankings demonstrates that the proposed model is not critically dependent on a single parameter and is suitable for preliminary technology selection under conditions of limited data. This robustness supports the applicability of the approach for analytical decision-making in inclusive and educational contexts.

6 Scenario-Based Evaluation Setup

In order to ensure the methodological consistency of the multi-criteria analysis and to avoid ambiguity in the interpretation of results, a standardized scenario-based evaluation setup was applied for comparing technologies for the formation of tactile educational materials. The proposed setup corresponds to the *design-time* decision-making stage, where physical experimental testing of samples is limited, unavailable, or economically impractical. Such conditions are typical for educational institutions, rehabilitation centers, and resource-constrained environments.

The study is analytical rather than experimental and is aimed at supporting technology selection instead of laboratory verification of physical artifacts. The comparison of alternatives is performed within a single conditional scenario based on agreed technical characteristics, descriptions of technological capabilities reported in the literature, and engineering assumptions relevant to practical contexts of use. This approach is characteristic of AHP–Fuzzy decision-support models, where the primary value lies in the structured comparison of alternatives rather than in direct measurement of individual physical parameters.

6.1 Scenario Definition and Evaluation Protocol

The evaluation of Braille formation technologies was conducted within a single standardized scenario corresponding to the production of tactile learning materials for resource-constrained educational environments. The scenario defines typical requirements related to the geometric quality of tactile relief, speed of material preparation, availability of infrastructure, and flexibility of content adaptation.

To ensure consistency across alternatives, all technologies were evaluated against a fixed set of criteria and standardized linguistic scales. The characteristics of each alternative were interpreted as analytically generalized estimates formed on the basis of:

1. technical descriptions and results reported in previous studies;
2. typical engineering parameters commonly accepted in industrial practice;
3. generalized scenario assumptions related to operation, maintenance, and institutional constraints.

The evaluation does not rely on newly collected empirical measurements or user-centered studies. Instead, it synthesizes reference technological configurations and analytically justified assumptions derived from international standards, manufacturer specifications, and peer-reviewed literature. This approach is consistent with decision-support models applied during early design stages, where the primary objective is structured comparison rather than physical verification.

6.2 Reference Technological Configurations

To ensure comparability, each technology was represented by a reference configuration commonly described in the literature and widely available in practice.

FDM printing. The evaluation was based on typical industrial parameters, including a nozzle diameter of 0.4 mm, layer height of approximately 0.12 mm, and geometric accuracy in the range of 100–150 μm. These parameters reflect inherent limitations of FDM technology, such as surface layering effects and sensitivity to calibration and material stability.

SLA/DLP printing. The evaluation relied on characteristics of resin-based UV printers with layer heights below 0.05 mm, which are generally considered an industry standard for the production of small, high-precision tactile components.

Mechanical embossing and thermoforming. The characteristics of these technologies were interpreted based on publications from manufacturers and research centers describing the stability of dot geometry, durability of tactile relief, and high speed of material preparation.

Other technologies. Tactile inkjet printing, electronic tactile displays, and manual Braille methods were evaluated using generalized technical profiles derived from open technical documentation, standards, and scientific publications.

6.3 Geometric Reference Standard

All evaluated technologies were assessed with respect to their ability to form Braille cells compliant with the standards defined by the Braille Authority of North America

(BANA). In particular, the following geometric parameters were adopted as reference values:

- dot height of approximately 0.48 mm;
- dot diameter of approximately 1.44 mm;
- inter-dot spacing of approximately 2.34 mm.

The use of a unified geometric reference standard ensures the correctness and comparability of alternative evaluations within constraints that have direct practical relevance for tactile readability and user perception.

6.4 Treatment of Uncertainty and Sensitivity Analysis

Uncertainty in expert assessments was modeled using triangular fuzzy numbers within the Fuzzy AHP framework. To evaluate the robustness of the obtained rankings, a sensitivity analysis was performed by varying the weights of the evaluation criteria within a range of $\pm 10\%$.

The results demonstrate that moderate variations in criteria weights do not lead to changes in the ordering of the highest-priority alternatives. This indicates that the proposed model is stable and does not critically depend on a single dominant parameter. Such robustness is particularly important for decision-making in the field of accessibility, where contextual constraints and subjective assumptions are unavoidable.

7 Discussion

The obtained results demonstrate consistent trends in the behavior of different classes of Braille formation technologies and are in agreement with conclusions reported in previous studies on tactile graphics and Braille production [6, 40]. Traditional technologies, including paper embossing and mechanical embossing presses, achieved the highest integral scores. This outcome is primarily explained by the stability of the tactile relief, minimal variability in dot geometry, and the ability to rapidly replicate materials in mass production scenarios.

Mechanical devices such as the Perkins Brailler provide reliable tactile accuracy and predictable geometric compliance. However, they are inferior to digital technologies in terms of flexibility and speed of content adaptation. Their application is therefore most appropriate in stable educational environments with fixed curricula, while being less effective for individualized or frequently updated materials.

Additive manufacturing technologies form a distinct group characterized by pronounced trade-offs. SLA/DLP technologies demonstrate high precision in relief formation, confirming their suitability for complex tactile models and dense information layouts [12, 41]. At the same time, the high cost of equipment, materials, and post-processing procedures limits their applicability in mass or time-critical production scenarios. In contrast, FDM technologies remain affordable and relatively easy to operate, but exhibit lower repeatability and reduced stability of tactile relief, which negatively affects long-term tactile readability [11, 29].

Electronic tactile displays achieved high scores with respect to information quality and access speed. These results are consistent with characteristics reported in both

classical micromechanical implementations and modern energy-efficient solutions [42–44]. Nevertheless, their practical use is constrained by high cost, limited scalability, and restricted display area, which reduces their suitability for large-format tactile materials or mass dissemination.

To support further interpretation of the results, clustering of technologies was performed in a reduced feature space using principal component analysis (PCA), as shown in Figure 11. The resulting distribution reflects structural similarity of alternatives across the selected criteria and confirms that the proposed model produces not only a linear ranking, but also a coherent multidimensional representation of the technological landscape. Three main clusters were identified: stable traditional methods; high-precision digital solutions; and economically accessible but less accurate approaches.

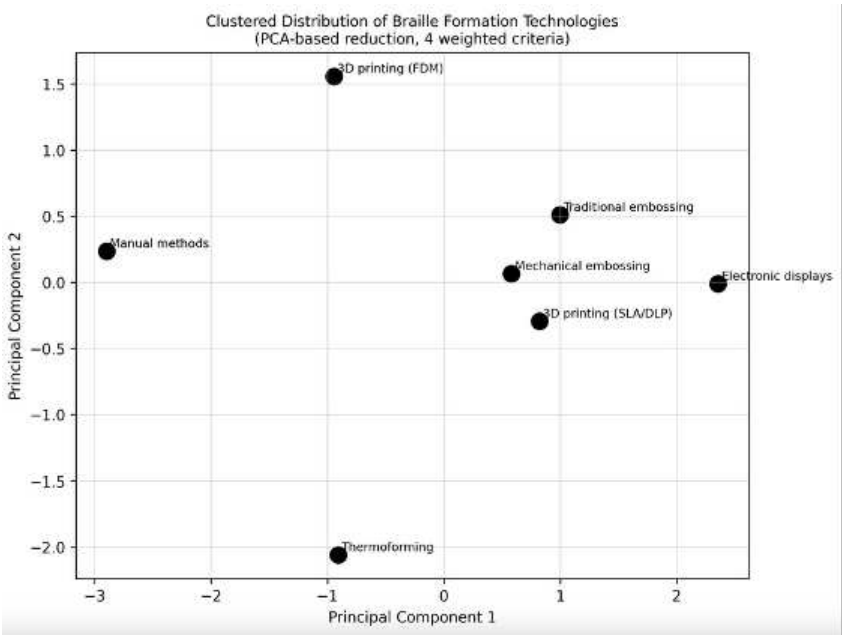


Fig. 11 Clustered distribution of seven Braille formation technologies based on four weighted criteria: quality, speed, cost, and flexibility.

The observed clustering confirms that the Fuzzy AHP approach not only generates an ordered ranking of alternatives, but also adequately captures internal similarities between technologies in a multidimensional decision space. Comparison with related studies shows strong consistency: relief stability remains critical for fast tactile reading; SLA technologies demonstrate advantages in complex geometries; FDM retains its role as an affordable baseline solution; and electronic displays provide high quality under significant economic constraints [19, 33]. Similar conclusions reported in studies on additive manufacturing and assistive technology selection further confirm the suitability of multi-criteria decision models for inclusive design tasks [45, 46].

Overall, the proposed analytical framework provides a formalized and transparent mechanism for technology selection under multi-criteria constraints. By structuring expert knowledge and making the reasoning process explicit, the framework aligns with the principles of universal access, transparency, and inclusion. This is particularly relevant for educational and governmental settings, where technology choices directly affect accessibility and quality of tactile information for visually impaired users.

In summary, the results confirm that no single Braille formation technology is universally optimal. The appropriate choice depends on the application context, including requirements for mass production, customization, budget limitations, level of geometric detail, and educational objectives. The proposed model supports informed decision-making by enabling a balanced consideration of these factors in practical scenarios.

8 Limitations

The present study has several limitations resulting from its analytical and scenario-based nature. The evaluation is grounded in generalized technical characteristics and expert-based assumptions rather than direct physical testing of produced tactile samples. As a result, fine-grained variations in tactile perception, particularly for high-precision additive manufacturing technologies and electronic tactile displays, are not explicitly captured.

Furthermore, the decision model incorporates four key evaluation criteria. While these criteria are sufficient for pre-selection and comparative analysis in educational and institutional contexts, additional parameters such as long-term durability, material aging, energy consumption, and maintenance requirements may be relevant in specialized application scenarios.

Despite these limitations, the proposed approach is well suited for the early stages of technology selection, where empirical testing is infeasible or economically impractical. The framework provides a structured basis for narrowing the range of alternatives prior to experimental validation and can be extended in future work by incorporating empirical measurements and user-centered evaluations.

9 Conclusion

This study proposed a reproducible decision-support framework for the selection of Braille formation technologies in the context of universal access. In contrast to isolated comparisons of individual technologies, the approach integrates multi-criteria evaluation, fuzzy uncertainty modeling, and transparent aggregation of results within a single analytical framework.

The results indicate that none of the considered technologies can be regarded as universal across all usage scenarios. Traditional mechanical methods remain effective for stable mass production of tactile materials, whereas additive manufacturing technologies provide higher flexibility and individualization at the cost of increased preparation time and resource sensitivity. These findings confirm the feasibility of applying formalized decision-support tools in inclusive education and accessible

design practices, where technological choices directly affect learning efficiency, tactile readability, and navigation safety [47–49].

The proposed framework shifts the focus from technology-specific optimization toward scenario-oriented prioritization, enabling institutions to justify technology choices under conditions of limited empirical data. Further research may extend the model by incorporating direct user assessments and integrating experimental measurements of tactile characteristics for specific production scenarios, thereby strengthening the connection between analytical evaluation and physical validation.

Supplementary information. The input matrices (criteria pairwise comparisons and fuzzy evaluation tables) and the complete computational notebook (Jupyter/-Google Colab) are provided as supplementary materials to enable independent reproduction of the results. Additional materials may be shared by the corresponding author upon reasonable request.

Declarations

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Author Contributions. All authors contributed to the conception and design of the study. Nikita Tarasov performed the preparation of materials, conceptualization, analytical modeling, computational implementation, and validation of the decision-support system. Orest Khamula analyzed and reviewed the manuscript and research results and commented on the manuscript, contributing to the improvement of the research. All authors reviewed and approved the final manuscript.

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Institutional Review Board Statement. Not applicable.

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Data Availability. All data required to reproduce the results are provided in the supplementary materials, including the complete computational notebook and all input matrices used in the AHP–Fuzzy evaluation.

Code Availability. The complete Jupyter-compatible notebook (Jupyter/Google Colab), including the full workflow for generating figures, processing expert evaluations, and reproducing the multi-criteria ranking results, is provided as supplementary material.

Conflict of Interest. The authors declare no conflicts of interest.

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