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ORDERING THE INFLUENCING FACTORS OF THE 3D PRINTING PROCESS USING THE RANK CORRELATION METHOD

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For the development of experimental research on the Fused Deposition Modeling (FDM) process, a critical preliminary step is the selection of input factors whose variation significantly influences the output parameters. Given the inherently large number of potential factors in FDM, a method for narrowing down this set to a manageable number for experimental activities was required. To address this, the rank correlation method was employed. This approach enabled the ordering of input factors based on a mathematical processing of expert opinions in the field, thus providing a rational basis for the subsequent experimental design.

Keywords: fused deposition modeling, additive manufacturing, process parameters, input factors, rank correlation, expert survey, factor selection.

1. Introduction

Manufacturing processes are technologically classified into three fundamental categories [1]. *Additive processes*, such as Additive Manufacturing (AM), synthesize components through the layered deposition of material.

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Subtractive processes, like machining, achieve the desired geometry by the controlled removal of material from a blank. *Forming* or *state modification processes*, such as precision forging or heat treatment, alter the shape or properties without significantly changing the mass of the blank.

Additive Manufacturing (AM) processes encompass technologies such as Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Stereolithography (SLA), Electron Beam Melting (EBM), etc. These processes share the basic principle of additive manufacturing, which involves building objects layer by layer based on a digital 3D model, without the need for specific tools or molds.

The Fused Deposition Modeling (FDM) process is defined as an additive manufacturing technology that produces parts by extruding and selectively depositing a thermoplastic material in filament form in a molten state onto a suitable platform, in the form of successive layers that contribute to generating the contour and infill of the 3D object.

The main output parameters of the FDM process are the mechanical properties of the manufactured part's material, such as tensile and impact strength, dimensional accuracy, surface roughness, and the degree of structural anisotropy. These parameters are directly determined by the controlled input factors in the process. The main input factors include some thermal parameters (extruder and platform temperature), kinematic parameters (extrusion and travel speeds), geometric parameters (layer height and infill density), and the properties of the thermoplastic filament material. The interaction between these input factors defines the final characteristics of the manufactured product.

Research in the field has demonstrated a systematic and complex correlation between the values of the input factors in the FDM process and the values of the output parameters [2,3]. Studies have shown that thermal parameters, such as nozzle and platform temperature, decisively influence interlayer adhesion and mechanical strength, with optimal temperatures reducing porosity and improving fracture resistance. Geometric parameters, such as layer height and orientation angle, have a critical impact on surface roughness and dimensional accuracy, with specific orientations minimizing the generation of superficial stair-stepping artifacts. In parallel, extrusion speed and travel speed integrally affect the material flow state and the geometric integrity of the future part, and non-optimized settings lead to defects such as under-extrusion or material overflow.

The objective of the research was to identify and rank the process factors with a significant influence on the output parameters in FDM technology. The aim was to validate a methodology for selecting critical factors by applying the rank correlation method, based on the evaluations of an expert panel. The results aimed to establish an experimental basis for the efficient optimization of the additive manufacturing process.

This paper presents the application of the rank correlation method as a systematic tool for prioritizing input factors in Fused Deposition Modeling. By mathematically processing expert assessments, a validated ranking of the most influential parameters was established. The resulting hierarchy, confirmed through relevant statistical indicators, offers a clear and empirically grounded rationale for selecting the critical factors to be investigated in future experimental studies, thus ensuring the efficiency and relevance of the subsequent research activities.

2. Systemic Analysis of the 3D Printing Process

The FDM process consists of melting a thermoplastic material filament and extruding it through a heated nozzle, which moves precisely on three axes to deposit the material layer by layer, where it subsequently solidifies. These layers adhere to each other, including through thermal contraction, progressively building the 3D object on a platform, which is usually heated to improve adhesion. After printing is completed, the part is removed from the platform, and finishing operations may be required, such as the removal of supports or bursts, or sanding.

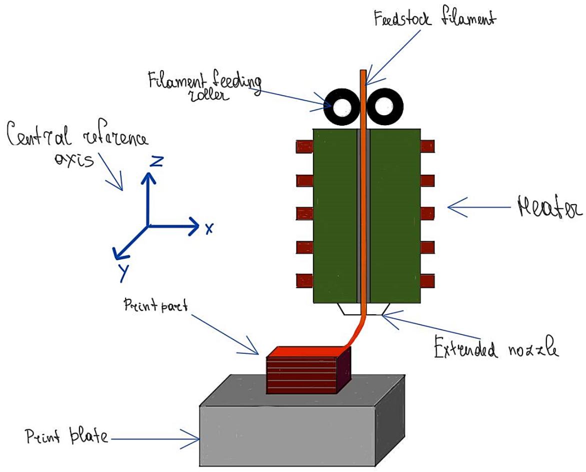

Fig.1. Schematic representation of the FDM Process *(original drawing by the authors)*. The input factors analyzed are listed in Table 1.

In Table 1, each of the 10 experts assigned ranks from 1 (most influential) to 9 (least influential) to the nine input factors ($x_1 ... x_9$). For each factor, the sum of the ranks assigned by all experts was calculated and denoted A_j. Based on these sums, an initial ranking $Q_j(1)$ was established, where the factor with the smallest A_j received rank 1, indicating the strongest perceived influence.

Table 1

Initial data regarding the factors influencing the output parameter values of the 3D printing process

Expert nr.	Influencing factors, x_k								
	x_1 (nozzle temperature)	x_2 (bed temperature)	x_3 (layer height)	x_4 (print speed)	x_5 (cooling fan speed)	x_6 (infill percentage and pattern)	x_7 (extrusion width)	x_8 (nozzle diameter)	x_9 (filament material type)
1	7	8	4	1	9	2	6	5	3
2	5	9	4	3	8	1	6	7	2
3	2	3	4	8	9	7	5	6	1
4	4	6	8	2	7	5	3	9	1
5	8	9	3	5	6	4	2	7	1
6	5	9	3	6	8	2	7	4	1
7	6	8	4	6	9	2	4	4	2
8	6	8	4	3	8	2	6	5	3
9	6	8	5	3	9	1	7	4	2
10	5	9	8	6	2	1	3	8	2
A_j	54	77	47	43	75	27	49	59	18
$Q_i(1)$	7	8	4	1	9	2	6	5	3

In Table 1, for each factor x_j, the sum of the ranks assigned by all 10 experts was calculated and denoted as A_j (e.g., for factor x_1, $A_1 = 7+5+2+4+8+5+6+6+6+5 = 54$). Based on these sums, an initial ranking $Q_j(1)$ was established, where the factor with the smallest A_j (indicating the highest perceived influence) received rank 1, the next smallest received rank 2, and so on.

The main input factors analyzed in this study—denoted as x_1 through x_9—correspond to the process parameters listed in Table 1. These parameters influence various stages of the FDM process illustrated in Figure 1, such as material extrusion, layer deposition, and solidification.

The Fused Deposition Modeling process is influenced by a wide array of factors, typically spanning material properties, process parameters, part design, and environmental conditions. Consequently, a wide range of output parameters, from mechanical performance to surface quality and productivity, can be affected. The primary challenge in designing experimental research lies in selecting, from this multitude, the specific input factors whose variation is most likely to induce significant changes in the outputs of interest. This study addresses this challenge by focusing on the systematic selection of these critical factors.

3. The rank correlation method

Subsequently, systematic research is intended to be developed to quantify the influence and the strength of the relationship between the input factors of the FDM process and critical output parameters, such as the physical and mechanical properties of the finished parts. This endeavor requires the application of the rank correlation method to order the influencing factors and establish certain priorities in the optimization of the manufacturing process.

In principle, the rank correlation method consists of replacing the numerical values of the data with their order ranks and measuring the relationship between variables based on these ranks [4]. It evaluates whether an increase in the rank of an independent variable (the value of an input factor) is associated with an increase or a decrease in the rank of the dependent variable (the value of the output parameter), expressing the identified connection through a coefficient. This coefficient, whose value varies between -1 and +1, thus indicates the strength and direction of the monotonic relationship between the two sets of ranks.

The main steps followed in using the rank correlation method are collecting paired data for the two variables and assigning ranks to this data, from 1 for the smallest value upwards [4]. The next step involves calculating the differences between the corresponding ranks for each data pair. These differences are retained and summed, and the resulting sum is inserted into the specific formula for the rank correlation coefficient, such as Spearman's formula. Finally, the calculated value of the coefficient is interpreted to determine the strength and direction of the relationship between the variables.

4. Using the Rank Correlation Method for Ordering the Input Factors in the FDM Process

For the FDM process, nine important input factors were considered, having a significant influence on the properties of printed parts: nozzle temperature (x_1), bed temperature (x_2), layer height (x_3), print speed (x_4), cooling fan speed (x_5), infill percentage and pattern (x_6), extrusion width (x_7), nozzle diameter (x_8), and filament material type (x_9). These parameters cover critical influences on mechanical properties, dimensional accuracy, surface condition, and productivity of the 3D printing process.

A panel of 10 experts evaluated these factors, assigning ranks from 1 (most influential) to 9 (least influential). Their complete rankings are presented in Table 1. Based on the sums A_j calculated in Table 1 (where A_j represents the total of ranks assigned to each factor), an initial ordering of factors was obtained, as shown in Table 2. In this table, $Q_j(1)$ represents the initial ranking, where the factor with the smallest A_j received rank 1.

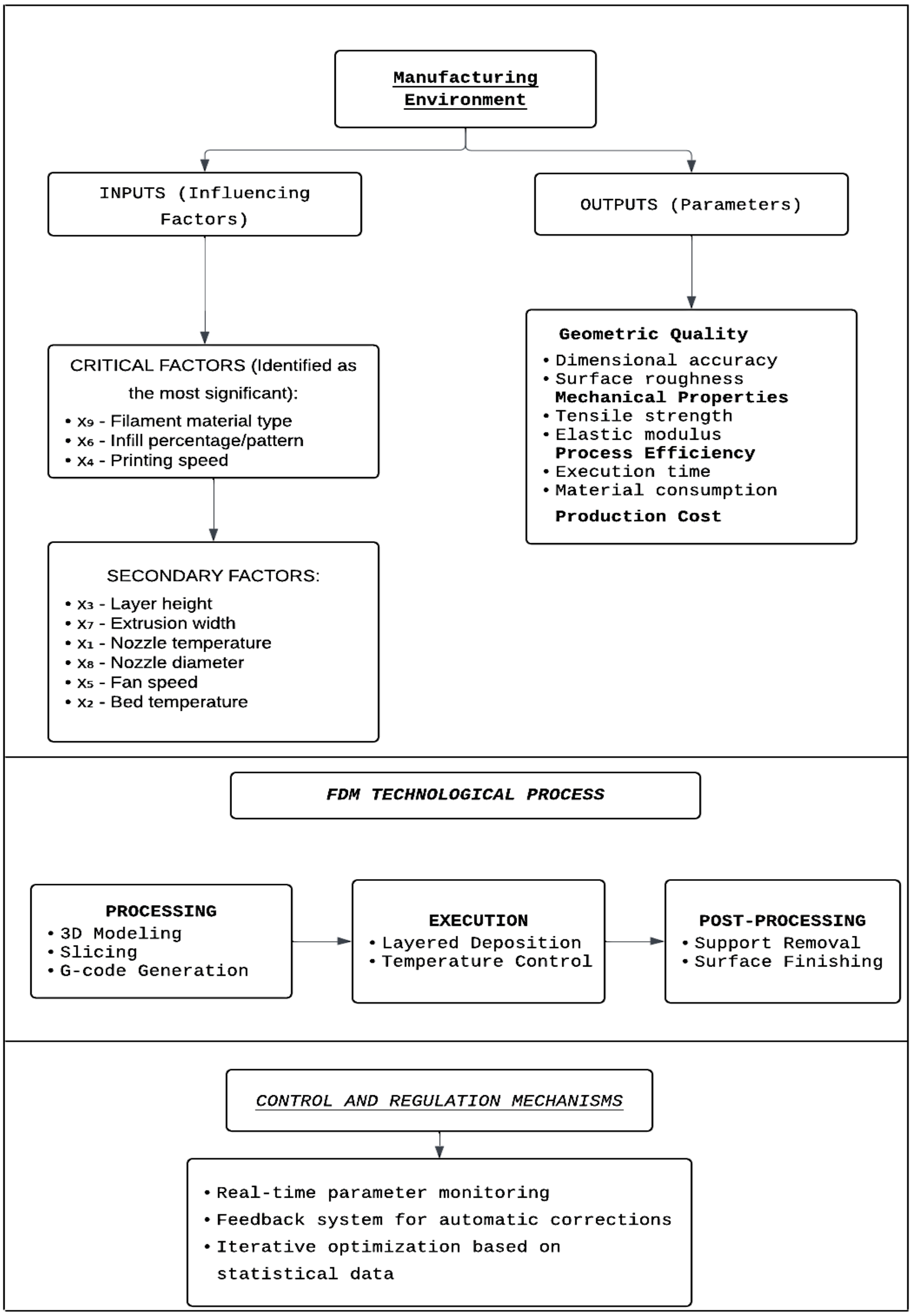

Fig. 2. Schematic representation resulting from the application of the systemic analysis method to the FDM process

The 9 input factors for the FDM process from Table 1, evaluated by the experts, are: nozzle temperature, bed temperature, layer height, print speed, cooling fan speed, infill percentage and pattern, extrusion width, nozzle diameter, and filament material type. Figure 2 illustrates the systemic context in which these factors operate, showing how they integrate into the overall FDM process and relate to the output parameters. This visual framework supports the subsequent ranking procedure by highlighting the complex interactions that justify a structured prioritization of factors. A group of 10 experts in the FDM field (specialists with specific experience in the domain) ranked these factors according to their influence on the output parameter values of the process. Following the analysis, the most influential factors proved to be the filament material type, the infill percentage and pattern, and the print speed.

In the second stage, table 2 presents the factors ordered according to the increasing values of A_j, along with their corresponding initial ranks $Q_j(1)$.

Table 2

Initial ranking

Factor	x_9	x_6	x_4	x_3	x_7	x_1	x_8	x_5	x_2
A_j	18	27	43	47	49	54	59	75	77
Q_i (1)	1	2	3	4	5	6	7	8	9

In the third stage, when multiple factors receive the same rank from an expert, a correction is necessary to ensure accurate calculations. For each expert with tied ranks, the ranks are adjusted by averaging the positions they occupy. This procedure is applied below for Experts 7 and 10.

It is found that such a situation corresponds to Expert 7, whose indicated ranks were: 6, 8, 4, 6, 9, 2, 4, 4, 2.

Factors x_3 ,x_7, x_8 occupy positions 3, 7, and 8. The sum of the ranks is 3+7+8=18. Since the number of factors assigned to the same rank was 3, the corrected rank will be 18/3 = 6.0.

For rank 6, initially assigned to factors x_1 and x_4 (occupying positions 1 and 4), the sum of the ranks will be 5. Since there are two factors proposed for the same rank (number=2), the corrected rank (determined by dividing the sum of the ranks by the number of factors with the same rank) will have a value of 2.5.

Rank 2 was assigned to factors x_6 and x_8, occupying positions 6 and 9, so the sum of the ranks is 15. Since the number of factors at rank 2 was 2, the corrected rank 15/2=7.5 is obtained.

Under the new conditions, with corrected rank values, the initial positions from Expert 7's case are modified as follows:

x_1=6 → 2.5, x_2=8 → 9, x_3=4 → 6.0, x_4=6 → 2.5, x_5=9 → 10, x_6=2 → 7.5, x_7=4 → 6.0, x_8=4 → 6.0, x_9=2 → 7.5

Equal ranks are also found in the case of expert 10, for whom the initial order was: 5, 9, 8, 6, 2, 1, 3, 8, 2. Rank 8 was assigned to factors x_3 and x_8, located at positions 3 and 8, with the sum of the ranks being 3 + 8 = 11. Since the number of factors with the same rank was 2, the corrected rank will be 11/2 = 5.5.

Additionally, expert 10 assigned rank 2 to factors x_5 and x_9, located at positions 5 and 9. The sum of these ranks is 5 + 9 = 14, and since the number of factors initially assigned the same rank was 2, the corrected rank will be 14/2 = 7.0.

The new valid ranks for expert 10 will be:

x_1=5 → 4, x_2=9 → 9, x_3=8 → 5.5, x_4=6 → 6, x_5=2 → 7.0, x_6=1 → 1, x_7=3 → 3, x_8=8 → 5.5, x_9=2 → 7.0.

It is found that there are no other experts who assigned equal ranks to multiple factors. This leads to the information in secondary table 3, which includes the corrected ranks.

The corrected ranks for all experts are presented in Table 3. Based on these corrected values, new sums A_j were recalculated for each factor.

Table 3

Secondary table with corrected ranks

Expert	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
1	7	8	4	1	9	2	6	5	3
2	5	9	4	3	8	1	6	7	2
3	2	3	4	8	9	7	5	6	1
4	4	6	8	2	7	5	3	9	1
5	8	9	3	5	6	4	2	7	1
6	5	9	3	6	8	2	7	4	1
7	2.5	9	6.0	2.5	10	7.5	6.0	6.0	7.5
8	6	8	4	3	8	2	6	5	3
9	6	8	5	3	9	1	7	4	2
10	4	9	5.5	6	7.0	1	3	5.5	7.0
A_j	49.5	78	46.5	38.5	81	33.5	51	59.5	28.5

Using the corrected sums A_j from Table 3, a new ranking $Q_j(2)$ was established, following the same principle: the smallest A_j receives rank 1, indicating the highest influence. This secondary ranking is shown in Table 4.

Table 4

Secondary table ranking ($Q_j(2)$)

Factor	x_9	x_6	x_4	x_3	x_7	x_1	x_8	x_5	x_2
A_j	28.5	33.5	38.5	46.5	49.5	51	59.5	78	81
Q_j (2)	1	2	3	4	5	6	7	8	9

For the calculation of Spearman's correlation coefficient r_s, the following relation is used [5]:

$$r_s = 1 - \frac{6}{k^3-k}\sum_{j=1}^{k}\left[Q_j(1) - Q_j(2)\right]^2, \quad (1)$$

where the number of factors taken into consideration is k=9.

To evaluate the consistency between the initial ranking $Q_j(1)$ and the corrected ranking $Q_j(2)$, the difference $d_j = Q_j(1) - Q_j(2)$ was calculated for each factor. The squared differences d_j^2 are used in computing Spearman's correlation coefficient. These values are presented in Table 5.

Table 5

Differences between initial and corrected rankings

Factor	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
$Q_j(1)$	6	9	4	3	8	2	5	7	1
$Q_j(2)$	5	8	4	3	9	2	6	7	1
d_j	1	1	0	0	-1	0	-1	0	0
d_j^2	1	1	0	0	1	0	1	0	0

According to the values in Table 5, the sum of the squared differences is $d_j^2 = 4$.

Spearman's rank correlation coefficient r_s measures the similarity between two rankings. It is calculated using the formula:

$$r_s = 1 - \frac{6 \cdot 4}{9 \cdot (81 - 1)} = 1 - \frac{24}{720} = 1 - 0.0333 = 0.9667$$

It is found that $r_s = 0.967$ is a value very close to 1, which means that the rankings are very similar.

The consensus coefficient W (Kendall's coefficient of concordance) measures the agreement among the 10 experts. It is calculated using the formula:

$$W = \frac{12 \sum_{j=1}^{k} \Delta_j{}^2}{m^2(k^3 - k) - m \sum_{i=1}^{m} T_i}, \tag{2}$$

where:

$$\Delta_j = \sum_{i=1}^{m} a_{ij} - \frac{m(k-1)}{2}. \tag{3}$$

A value of W close to 1 indicates strong agreement, while a value close to 0 indicates weak agreement.

Next, the values $T_i = \sum(t^3 - t)$ are calculated for the tied ranks of each expert i.

Several m = 10 experts are considered, who initially performed the ranking of a number $k = 9$ factors.

Stage 1: the calculation of the difference values Δ_j is required.

$$M = \frac{m(k+1)}{2} = 100/2 = 50 \tag{4}$$

The sum of the A_j values calculated down the column in Table 3 with the corrected ranks will consider the values:

$A_j = [49.5 ,78 ,46.5 ,38.5 ,81 ,33.5 ,51 ,59.5 ,28.5]$

The differences Δ_j will therefore be:

$\Delta_j = A_j - 50 = [-0.5, 28 , -3.5 , -11.5 , 31 , -16.5 , 1 , 9.5 , -21.5]$

The squares of these differences will be:

$$\Delta_j{}^2 = [0.25,784,12.25,132.25,961,272.25,1,90.25,462.25]$$

The sum of the squares of the differences Δ_j will be:

$$\sum \Delta_j{}^2 = 2715.5$$

Stage 2: the T_i values are calculated. It is found that only experts 7 and 10 assigned equal ranks. This means that:

- In the case of expert 7, it is found that 4 sets of ties (t=3) are reached, $t^3 - t = 24$, and ranks 6 (t=2), meaning 6 ranks with t=2, and this will lead to a value of 6. His value will be T_7 = 36.

- In the case of expert 10, it is obtained, similarly: ranks 8 (t=2) leading to the value 6; ranks 2 (t=2) leading to a value of 6, and this means that T_{10}= 12 is obtained.

For the other experts, it is found that T_i= 0. The sum of the Ti values will therefore be:

$$\sum T_i = 36 + 12 = 48.$$

Stage 3: the value of the consensus coefficient W is calculated:

$$W = \frac{12 \cdot 2715.5}{100 \cdot (729 - 9) - 10 \times 48} = \frac{32586}{72000 - 480} \approx 0.4556$$

In an eighth stage, the significance of the consensus is tested. Since the number of factors k = 9 is greater than 7, the chi-square (χ^2) approximation is used instead of special tables for Kendall's W. The test statistic is calculated as:

$$\chi_{calc}{}^2 = m(k-1) \cdot W = 10 \cdot (9-1) \cdot 0{,}4556 = 36.448 \quad (5)$$

The number of degrees of freedom considered is $\nu = k - 1 = 8$.

From the tables valid for the $\chi_{calc}{}^2$ criterion, the tabulated value $\chi^2(8;\ 0.05) = 15.51$ is obtained.

Since 36.448 > 15.51, it can be concluded that there is a significant consensus.

As a ninth and final stage, significance indices I_j were calculated to express the relative importance of each factor on a scale from 0 to 100. Higher values indicate greater influence. The significance indices I_j are calculated using the relation:

$$I_j = K \cdot \frac{k+1-Q_j(2)}{\sum_{j=1}^{k}(k+1-Q_j(2))}, \quad (6)$$

where K = 100.

$$Q_j(2) = [5,8,4,3,9,2,6,7,1]$$

$$k + 1 - Q_j(2) = [5,8,4,3,9,2,6,7,1]$$

The sum of the ranks is 45, which allows for the calculation of the significance indices values:

$I_j = 100 \cdot \frac{k+1-Q_j(2)}{45}$:

- $I_1 = 100 \cdot \frac{5}{45} \approx 11.11$
- $I_2 = 100 \cdot \frac{2}{45} \approx 4.44$
- $I_3 = 100 \cdot \frac{6}{45} \approx 13.33$
- $I_4 = 100 \cdot \frac{7}{45} \approx 15.56$
- $I_5 = 100 \cdot \frac{1}{45} \approx 2.22$
- $I_6 = 100 \cdot \frac{8}{45} \approx 17.78$
- $I_7 = 100 \cdot \frac{4}{45} \approx 8.89$
- $I_8 = 100 \cdot \frac{3}{45} \approx 6.67$
- $I_9 = 100 \cdot \frac{9}{45} \approx 20.00$

The arrangement of factors in descending order by considering the significance of index values is as follows:

$$x_9(20.00), x_6(17.78), x_4(15.56), x_3(13.33),$$
$$x_1(11.11), x_7(8.89), x_8(6.67), x_2(4.44), x_5(2.22)$$

As a final result, it was concluded that the most significant factors are x_9 (filament material type), x_6 (infill percentage and pattern), and x_4 (printing speed), for which the experts' consensus is significant ($\chi^2_{calc} > \chi^2_{tabelat}$) and the correlation between the values in the initial table and the corrected values is very good ($r_s \approx 0.967$).

5. Conclusions

This study aimed to apply the rank correlation method to identify and rank significant influencing factors in the FDM manufacturing process. The consensus of expert opinions was evaluated to determine the factors with a major impact on the process output parameter values. The obtained results enable process optimization by focusing attention on the most influential factors identified.

A clear hierarchy of influencing factors was identified, with filament material type, infill percentage, and printing speed emerging as the most significant input factors. This ranking provides a empirically-grounded foundation for prioritizing process parameters in subsequent experimental investigations. The statistical analysis confirmed a strong consensus among the experts. The Spearman correlation coefficient between the initial and corrected rankings was $r_s = 0.967$, indicating a very high similarity. Kendall's coefficient of concordance was W=0.4556, and the chi-square test ($\chi^2_{calc} = 36.448 > \chi^2_{tabelat} = 15.51$ for $\nu = 8$, $\alpha = 0.05$) demonstrated that this consensus is statistically significant.

The resulting hierarchy provides an empirically-grounded basis for prioritizing process parameters in future experimental investigations on FDM, enabling a more efficient approach to process optimization by focusing on the most influential factors identified in this study.

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